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A DISCUSSION ON METASOMATISM AND THE LINEAR "FORCE OF GROWING CRYSTALS."

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NEGLECTING the questions of the exact definition and scope of metasomatism,[1] both of which have recently been dealt with elsewhere,[2] this paper treats of the much less handled but very fundamental *processes,* or, in other words, the mechanism, of metasomatism.

Using the words Palasome[3] and Metasome for the terms "original mineral" and "metasomatic product," respectively, let a starting point in treatment of the subject outlined be the question, How does the metasome displace the palasome, and what is the nature of the processes involved? Are they physical, chemical, or both? To begin with, metasomatism involves the introduction and removal of matter at and from its site of action. This matter

[1] The synonymous word "replacement" is more familiar to English-speaking readers, but, as Lindgren has pointed out, metasomatism is susceptible of international use.

[2] W. Lindgren, Presidential Address, Geological Society of America, December, 1924.

[3] Palasome, from παλαιός, = old. Some explanation is due for the introduction of a new term. The English words "host" and "guest" suit admirably in connection with metasomatism, but since English-speaking readers appreciate the use by foreigners of terms that require no translation, it was thought better to set a lesson in this respect and use terms capable of international adoption in the hope that they will be generally used. Any one who has wrestled with the German words "Umbildung," "Neubildung," "Umsetzung," "Verdrängung," and been in doubt as to the exact meaning with which the author uses them, will appreciate the necessity for a common procedure in this matter.

has to be transported, and, therefore, transportation is an essential preliminary and accompanying condition of metasomatism. This phase has been considered at length in another place.[4] It is necessary to say, however, that our present knowledge of the subject is lamentably deficient.

Assuming suitable transportation, which will usually be by aqueous solutions of varying concentration, comparatively little difficulty is met with in considering metasomatism taking place near the surface, in open spaces, and, more generally speaking, within the zone of oxidation. Much greater trouble is met in finding acceptable and adequate explanation of metasomatism at greater depth where conditions, of pressure in particular, are so different.

In this paper attention will only be paid to metasomatism taking place beneath the zone of oxidation, but above that of plastic flow, *i.e.*, at the depths of the intermediate and deep zones of ore deposits. At the beginning it is necessary to know the nature of metasomatism. Is it amenable to the principles of thermodynamics, physics, and chemistry? Certainly, so far as can be seen, remembering the fact that thermodynamics takes no cognizance of time or mechanism, the fundamental thermodynamic laws must apply, but those nicely adjusted quantitative relations between heat, work, and energy represented by the usual thermodynamic equations are not applicable, nor will they be till there are introduced into them new variables of whose nature and number we at present know very little. Neither are the relations of the Phase Rule[5] (which are only qualitative) applicable to metasomatism with the usual restriction of the variables to temperature, pressure, and composition, and the exclusion of others, the most important of which geologically is surface.

In connection with the ability of physics to further the study of metasomatism, it is certain that more experimental work is

[4] H. C. Boydell, "The Rôle of Colloidal Solutions in the Formation of Mineral Deposits," *Bull. Inst. Min. and Met.* (London), December, 1924, p. 83.

[5] John Johnston and Paul Niggli, "The General Principles Underlying Metamorphic Processes," *Journal of Geology*, 21, 1913, p. 588. Wolfgang Ostwald, "Handbook of Colloid Chemistry," translation by M. H. Fischer, 1918, p. 106.

required in the directions of heat conduction, diffusion, stress, elasticity, earth currents, capillarity, etc., in rocks before much assistance is possible. Turning to chemistry, there will have to be full recognition on the part of chemists that the reactions of the test tube, beaker, and laboratory generally are not those applicable to geological processes as a whole and metasomatism in particular. Solubility, ionization, mass action, velocity of reaction, and solubility product relations must be adapted to geological conditions before chemistry will be able to tackle successfully metasomatism and other problems of geology.

Will chemists and physicists temper their sciences to the geological lamb that has hitherto fed from their hands, or will the geologist, perforce, laying aside for the nonce his petrology and paleontology, have to turn chemist and physicist, and of his own endeavor wrest from nature the keys to the explanation of the vast wealth of observed but unexplained facts that have accumulated in his own science, and at present are alike obscuring his vision and impeding his progress?

Let us try to define our metasomatic system. It may be considered to consist of a homogeneous palasome, and an aqueous solution containing, at least, one solute. Though the number of phases is two, the number of components is unspecified and our definition is, therefore, lacking in that essential respect.

What about temperature and pressure? A palasome mineral undergoing metasomatism within a mass of rock whose volume is enormously greater than that of the mineral itself can surely be regarded as under as near an approach to isothermal conditions as is possible of attainment.[6]

[6] If any one be inclined to question this statement and to say that the process is adiabatic, let him give some attention to a matter that the present writer does not remember to have previously seen raised. The operative solutions controlling the rate of metasomatic reaction in the mineral will be usually diffusing extremely slowly; heat will, therefore, be absorbed or given up by the surrounding rock at such a slow rate as to alter the temperature of surroundings to an extent that is wholly negligible; hence conditions will be essentially isothermal. On the other hand, though the rate of heat conduction in rocks is small, yet the reaction will proceed so slowly that the conductive power of the rock, small though it be, may well be able to take care of the accompanying heat change; hence the process can not be regarded as adiabatic.

The pressure, which will be high, may be regarded as constant at any one place, though it will probably vary from place to place.

Owing to the existent pressure, the system will have a strong tendency to be a condensed one, *i.e.*, one in which a gas phase is not present. It is to be remembered, too, that equilibrium will tend, owing to the conditions of pressure, in the direction of the suppression of a gas phase should one be formed. Our system thus consists of two phases, a solid and liquid; an indefinite number of components; the number of variables, while unknown, is certainly greater than the usual three, viz., temperature, pressure, and composition; of these the temperature and pressure are constant. It is impossible, therefore, to state the variance or number of degrees of freedom, and thus the state of the system, even if it be in equilibrium, can not be exactly defined. It would, of course, have been easy to take some definite assumed system consisting of palasome and intruding solution and thus have been able to state the number of components, but this would only have lent a fictitious precision and merely a misleading verisimilitude[7] of approximation to natural conditions, for the *number* of variables would still remain uncertain, and of the known ones, temperature and pressure, the dimensions could only be conjectured. In the foregoing nothing has been said about volume. If the system were a gaseous one, since pressure and temperature are constant, the volume (assuming no chemical reaction) would necessarily be constant also, but this is not the case in heterogeneous systems, such as the one under consideration. Generally, however, the volume change, if occurring, will be but slight.

In metasomatism three cases are possible:

Case I.—The metasome does not completely occupy the space previously filled by the palasome. In this event collapse, or

[7] A good illustration of what is meant by this is afforded by the long list of "Chemical Reactions" given by Van Hise in his "Treatise on Metamorphism" (pp. 375–394), which are purely hypothetical. One of these involves the change or disappearance of no less than *one hundred and eighty-two* reacting molecules!! Yet general chemical investigations show that reactions in which the concentrations of more than *three* reacting molecules undergo change (*i.e.*, more than three molecules disappear) are of comparatively rare occurrence and the rarity of reactions *increases* as the number of disappearing molecules involved in them increases.

"slumping," of the surrounding rock should take place, but the microscopic evidence shows that this does not usually happen.

Case II.—The metasome exactly fills the space previously occupied by the palasome. This is usually assumed to hold, and the case is commonly referred to as replacement (metasomatism) by equal volumes.[8] Available microscopic and field evidence justifies this assumption and shows that usually in metasomatism not only is there no "slumping," but that the metasome often faithfully preserves both the texture and structure of the palasome.

Since the molecular volumes of the metasome and palasome are rarely the same, it follows that the reaction involved in such a case does not take place in simple molecular ratio, *i.e.*, in the quantitative proportions of the chemical equation representing the reaction.

The present writer has suggested elsewhere[9] that this lack of stoichiometric relations might be met by supposing the metasomatic relations between palasome and metasome to be controlled by Freundlich's "adsorption equation." This would require the process to be essentially one of adsorption. Lindgren[10] considers metasomatism to be due to adsorption and supersaturation in capillary openings of the palasome. It was the writer's intention to test the applicability of the "adsorption equation" in the case of some simple metasomatic process carried out in open space, but it was finally considered impossible, in view of the small amounts of adsorbed material involved, to obtain results that would be free from the suspicion that they were vitiated by secondary reactions.

Case III.—The metasome takes up more space than the palasome, and makes room for itself by pushing apart or lifting up the surrounding rock. Intimately connected with this, though not necessarily involving the idea of metasomatism on the part

[8] W. Lindgren, "Mineral Deposits," McGraw-Hill, 1919, p. 70; also, ECONOMIC GEOLOGY, vol. 7, 1912, pp. 521–535; also, *Journal Geology*, vol. 26, 1918, pp. 542–555.

[9] H. C. Boydell, *op. cit.*, p. 82.

[10] W. Lindgren, "Mineral Deposits," McGraw-Hill, 1919, p. 26; also ECONOMIC GEOLOGY, vol. 7, 1912, p. 528.

of all its advocates, is the influence of the linear force of crystallization, or "force of growing crystals." This is held by some geologists to be a cause of the formation of veins and other forms of mineral deposits.

The first to do so was, so far as the writer knows, E. J. Dunn[11] in connection with the Bendigo Saddle reefs. Andrée[12] made use of the idea later, but its chief protagonists have been Taber[13] and Stillwell,[14] the latter of whom makes the most definite statement as to the magnitude claimed for the force of crystallization; he states, inter alia: ". . . The inference, therefore, appears to be that the magnitude of these forces (those of crystallization, HCB) is of the same order as those forces which are spoken of as crustal forces in geological literature and which are involved in mountain building movements."

The force (linear) of growing crystals has been accepted as a factor in Cornish vein formation by Weston-Dunn[15] and most recently by Rothrock[16] has invoked it to explain the presence of calcite in the Nussbaum formation of Cimarron County, Oklahoma. That growing crystals can exert linear force has been shown by Becker and Day[17] in spite of the statement to the contrary by Bruhns and Mecklenburg.[18] The former writers state ". . . this linear force, *because of the narrow rim through which it acts,* actually exerts a pressure of the same order of magnitude

[11] E. J. Dunn, Reports on the Bendigo Goldfield. Nos. 1 and 2, Special Reports, Dept. Mines, Victoria (Australia), 1896, p. 16. S. Taber gives references to C. G. A. von Weissenbach (1836) and J. Lavalle (1853). F. L. Stillwell also refers to Lachmann. These references were not consulted by the present writer.

[12] K. Andrée, Geologische Rundschau, 1912, No. 3, pp. 7–15. Gives bibliography.

[13] S. Taber, "Mechanics of Vein Formation," *Trans. Am. Inst. Min. Eng.,* vol. 51, 1915, pp. 3–36; also ECONOMIC GEOLOGY, vol. 13, 1918, pp. 538–546.

[14] F. L. Stillwell, ECONOMIC GEOLOGY, vol. 16, 1921, p. 157; also vol. 18, 1923, pp. 506–510.

[15] J. A. Weston-Dunn, ECONOMIC GEOLOGY, vol. 18, 1923, p. 451.

[16] E. P. Rothrock, *Journal Geology,* vol. 33, 1925, p. 80.

[17] G. F. Becker and A. L. Day, *Proc. Washington Acad. Sci.,* 7, 1905, pp. 283–288; also *Journal Geology,* vol. 24, 1916, pp. 313–333.

[18] W. Bruhns and Werner Mecklenburg (Clausthal), "über die sogennante Kristallizationskraft," Jahresbericht des Niedersächsischen geologischen Vereins zu Hannover, 6, 1913, p. 92.

as the breaking load of the solid crystals, need there be further hesitation in assuming that this is a force to be reckoned with in engineering, or in geology?" They found that growth was confined *to the periphery* of the supporting face of the crystal, and as this matter will be referred to later on it is as well to quote the authors' own words: ". . . It is then clear that the exposed top and side faces (or the side faces alone if the top is covered) may grow freely while the bottom remains more or less undernourished, *depending upon the load which is supported there* (the italics here and elsewhere, unless otherwise stated, are my own, H. C. B.), and the consequent impairment of circulation. Nevertheless, if the degree of supersaturation and the amount of material which is being furnished to the crystal through evaporation and diffusion is sufficient in quantity and *properly circulated,* the saturation concentration opposite that face also—that is, in the thin layer of liquid upon which the crystal rests—may be reached and the crystal may grow upon the bottom as well as upon the sides. Failure of the circulation in this supporting layer may, *and in fact, usually will restrict the growth here to the periphery of the supporting face,* causing it eventually *to rest upon a thin outer rim of new* growth rather than upon its initial flat surface, but growth will nevertheless take place here as elsewhere. The greater the crystal, the greater the weight supported upon its contact surface (or rim), and the greater, a fortiori, the difficulty of reaching the saturation concentration in any portion of the supporting layer and providing for further growth from the bottom." They also state further on: ". . . If the load upon the crystal is too great, or the rate of evaporation (the experiments were carried out in open glass vessels, H. C. B.) slow, *the saturation pressure may not be reached anywhere in the supporting liquid layer and growth here may be stopped. A still further increase in the load may even cause re-solution of the bottom surface, while the side surfaces continue to grow.*"

The distinct limitations imposed in the sentences in italics would seem to have been quite lost sight of by the advocates of the crystallizing force as a factor in vein formation. Taber[19]

[19] S. Taber, *Trans. Am. Inst. Min. Eng.*, vol. 51, 1915, pp. 3–36.

has claimed that additions may be made to the growing crystals ". . . at their bases where they are attached to the walls" by solutions containing material leached from the walls, and that in such cases the resulting products are columnar, acicular, or fibrous. The onus is certainly on him to show that, if this takes place in cases of vein formation where he invokes the force (linear) of growing crystals, with the pressure required solutions could diffuse in the wall at all, or if they could that they did so at a sufficient rate to keep a *supersaturated* layer in contact with the bases of the growing crystals. It is further incumbent on him to show that the openings through which the same solutions diffused would not form avenues of relief for the system from the growing pressure and also to explain the absence of the columnar, acicular, and fibrous structure from the resultant vein material of many mineral deposits.

The fundamental statement on which the theory of vein formation by the exertion of crystallization forces (linear) rests is that no force can prevent the growth of a crystal which is in contact with its own supersaturated solution. Such a contention at first sight even does not appear to be sound, for if it were so a system consisting of a crystal and its supersaturated solution would form a source of the impossible perpetual motion of the second kind. It is also opposed to known facts, since it implicitly states that no force can oppose the tendency of water to freeze and so expand when brought to 0° C., while it is well known that the freezing point of ice is lowered by pressure, and that ice also undergoes internal rearrangement which tends to counteract increase of pressure. It is thus opposed to Le Chatelier's theorem, according to which: "Whenever changes in the external condition of a system in equilibrium are produced, processes also occur within the system which tend to counteract the effect of the external changes."[20] The advocates of "the force of growing crystals" have overlooked, too, the very vital matter of the supply of necessary *supersaturated* solution to the growing crystal. Under the conditions of vein formation the solution can not be as-

[20] A. Findlay, "The Phase Rule," 1923, p. 46.

sumed to be kept saturated by simple evaporation of the solvent. By what means is the supersaturated solution supplied? This matter will be taken up in another connection later on and need not be further dealt with here. While general considerations of this kind point to the extreme improbability of linear crystallization force being able to produce the effect claimed for it in vein formation, there yet remains to be considered what the definite limiting conditions are.

Since crystalline growth under restraint results in the exertion of linear pressure on the surroundings, what effect, in addition to a lifting or separating one, would be produced by a growing crystal on its surroundings, or, to be more specific, in the wall rock of a vein?

Two results are possible if the pressure be sufficiently great. First, the melting point of the rock might be lowered by pressure to such an extent that it would melt; and, second, the "solubility" of the rock might be so raised by pressure that the rock would "dissolve" (melt) in moisture present.

Both these results are closely related, since the presence of moisture would materially lower the melting point of the rock, and, as Morey[21] (following Guthrie) has shown, solubility and fusion relations are intimately connected.

INFLUENCE OF PRESSURE ON THE MELTING POINT.[22]

In this connection it is necessary to distinguish between uniform (volume) and non-uniform (linear) or unequal pressure.[23] With the former, pressure is exerted equally on both the solid

[21] G. W. Morey, "Solubility and Fusion Relations at High Temperatures and Pressures," *Journal of the Engineers' Club of Philadelphia and Affiliated Societies*, November, 1918.

[22] A good recent treatment of this subject is given by E. Cohen and W. Schut in "Piezochemie kondensierter Systeme," 1919, p. 177 et seq.

[23] R. Mallet, *Philos. Trans. Royal Soc.* (London), 163, 1873, pp. 147–227, applied the matter geologically to the melting of rocks, and C. R. Van Hise, Mon. 47, U. S. Geol. Survey, 1904, p. 99, has given the subject general geological consideration.

John Johnston and L. H. Adams, "On the Effect of High Pressures on the Physical and Chemical Behaviour of Solids," *Am. Jour. Sci.*, (4), 35, 1913, pp. 205–253.

and liquid phase, and is hydrostatic in character. On the other hand, if the solid phase is subjected to greater pressure than is the liquid one, then the pressure is non-uniform (linear). A wine press, in which the grape juice is free to escape, affords a good example of non-uniform pressure. As can be predicted from the theorem of Le Chatelier, whether the melting point of a substance is raised or lowered by uniform (volume) pressure depends on whether its fusion is accompanied by increase or decrease of volume. Most substances fuse with increase of volume, hence their melting points are raised by uniform pressure. For metals the change is about 10° C. for each 1,000 atmos. of pressure. Water (and some other substances) is an exception to the rule, its fusion taking place with decrease of volume. The fusion point of ice is lowered 0.00075° C. for each atmos. of uniform pressure.

Generally speaking, the influence of uniform pressure on the melting point is small. This is not the case, however, with non-uniform (linear) pressure, which always results in a lowering of the melting[24] point, and the amount of the change greatly exceeds that produced by uniform pressure. In the case of ice, for example, the ratio of the influence on the melting point of non-uniform to uniform pressure is approximately 12:1. In this connection Johnston and Adams state: ". . . Indeed, if we make the plausible assumption that permanent deformation of a crystalline aggregate is conditioned by a real local melting (of those parts which at any moment bear the brunt of the load), we find the amount of pressure required to cause melting at ordinary temperature to be well within the bounds of probability. Such we believe to be the efficient cause in producing most of the phenomena recorded as occurring when solid systems are submitted to compression."

Johnston elsewhere[25] has given the lowering of melting point of some metals produced by 1 atmos. unequal (non-uniform) pressure as well as the unequal pressure required to melt the same

[24] J. Johnston and L. H. Adams, *op. cit.*, footnote on p. 213.

[25] John Johnston, *Jour. Am. Chem. Soc.*, vol. 35 (1), 1912, p. 792.

metals at 27° C. Silver, for example, with melting point 960° C. has its melting point raised 0.12° by 1 atmos. non-uniform pressure, and to melt it at 27° C. would require the application of 14,000 atmos. of unequal pressure, equivalent to a vertical depth from the surface of perhaps about 33 miles. Taking into consideration the generally high melting point of rocks, it is unlikely that non-uniform pressure, if exerted in metasomatism, would lead to fusion of the surrounding rock, and it is more unlikely that uniform pressure would do so, for, in the case of igneous intrusions, such as sills and dikes (which may be likened in their structural end results, at any rate, to the end results of vein formation by the force of crystallization), fusion effects or even incipient ones (except at the contact) in the overlying rock have not been reported and have almost certainly not taken place. Concerning the metasome, or the disappearing host, it may be asked could pressure effects in metasomatism, and particularly those due to non-uniform pressure, produce melting? Since in this case a liquid phase would also be present and would exert an influence on the melting point of palasome or metasome (or both), melting effects would approximate closely to those of solution and the case may be considered in connection with solution conditions.

EFFECT OF PRESSURE ON SOLUBILITY.[26]

Here again distinction must be made between the effects of uniform and non-uniform pressure.

Uniform Pressure.—The effect of this on the solubility of substances is slight. Increased pressure increases the solubility of those substances (and these form the great majority) whose going into solution is accompanied by decrease in *total* volume, while increase in pressure decreases the solubility of those substances which go into solution with increase in total volume.

Cohen and Schutt have found that the solubility of sodium chloride in water is increased 4 per cent. by a pressure of 1,500 atmos. at a temperature of 24° C.; that of $ZnSO_4$, $7H_2O$ is de-

[26] A good treatment of the subject is given by E. Cohen and W. Schutt, *op. cit.*, p. 374 et seq., but these authors do *not* treat of non-uniform pressure.

creased 0.7 per cent. by a pressure of 1,000 atmos. at 25° C.; and that of $CdSO_4$, $8/3H_2O$ is increased 3 per cent. by a pressure of 1,000 atmos. at 25° C.

Non-uniform (Linear) Pressure (or Stress).—Strange to say, though the effect on the *solubility* of a solid produced by the exertion on it of a greater pressure (linear) than that acting on the solvent with which the solid is in contact is occasionally referred to, there would not appear to exist in text books or works of reference generally any adequate treatment of the matter.

Some difference of opinion exists as to the sign and *magnitude* of the effect of non-uniform (linear) pressure on the solubility of a solid.

Johnston[27] in stating that considerations analagous to those he deals with in connection with the influence of non-uniform pressure on the melting point are also applicable to the influence of the same sort (linear) of pressure on the *solubility* of a solid means that the effect of non-uniform (linear) pressure on solubility much exceeds that of uniform (volume) pressure.

Le Chatelier (whose work is referred to at greater length further on) came to the same conclusion some twenty years prior to Johnston doing so.

More recently Hostetter[28] has stated that ". . . it is possible that fluctuating temperature and perhaps some indirect effects brought about by pressure may account for the modification of crystals compressed in contact with their solution by loosely fitting pistons as found by James Thomson, Le Chatelier, and Spring, without the necessity of postulating large increases of solubility due to pressure." As the result of preliminary experiments he considers that ". . . the effect of non-uniform pressure is much less than that produced by the same pressure acting uniformly and not many times greater as had been postulated by Johnston and Adams."

As will be seen from the mathematical treatment of the subject which follows, *both* the sign and the magnitude of the effect of

[27] John Johnston, *op. cit.*, p. 796.

[28] J. C. Hostetter, *Journ. Wash. Acad. Sciences*, 7, 1917, p. 79; also p. 195.

non-uniform (linear) pressure on the solubility of a solid depend in one case (of the two cases to be considered) on the molal volume of the solid and the partial molal volume of the same substance in solution and in the second case on the molal volume of the solid only.

In the first case the effect may be positive or negative, *i.e.*, non-uniform pressure may increase or decrease the solubility of a solid and the magnitude of the effect depends on the *difference* between the molal volume of the solid and the partial volume of the same substance in solution.

For the same solid, under the same conditions, the effect will always be the same.

In the second case, for all substances the effect is an increase in solubility that is approximately proportional to the pressure.

Williamson[29] has dealt with the effect of strain on heterogeneous equilibrium in a thorough and satisfactory manner. His mathematical treatment of the subject, following Gibbs, is more general and involved than the one that follows and lacks direct application to geological conditions, but his conclusions are substantially in agreement with those following.

Wright and Hostetter[30] have investigated the reversibility of the relations between a strained solid and its liquid. Their treatment is non-mathematical and shows that on crystallization each freshly deposited particle enters into the same state of strain as that which may exist in the crystal itself.

Le Chatelier[31] deals with the subject at greater length than anyone else, but the mathematical treatment is so brief and elliptical that it is difficult for the ordinary reader to follow, more particularly as he uses a notation unfamiliar at the present time. His work, however, is of great interest to the geologist, as he interpreted his deductions geologically and experimentally confirmed them in a qualitative way. He says, inter alia: ". . . Die Lösung dieser Angabe (investigation of unequal pressure—H.

[29] E. D. Williamson, *Physical Review*, 10, 1917, pp. 275–283.

[30] F. E. Wright and J. C. Hostetter, *Journ. Wash. Acad. Sciences*, 7, 1917, pp. 405–417.

[31] H. Le Chatelier, *Zeit. f. physik. Chemie*, 9, 1892, p. 335.

C. B.) giebt, wie ich zeigen werde, unmittelbar die Erklärung eines sehr allgemeinen geologischen Problems: das Zusammenbacken der aus pulverformigen Niedersclägen gebildeten Gesteine, welche sich auf der Erdoberfläche gebildet haben und sich noch gegenwärtig bilden. Mann kann so auf eine und dieselbe gemeinsame, einfache und vollkommen definirte Ursache die Bildung des Eises in den Gletschern aus dem Schnee, des festen Kalksteins und Marmors aus der Pulverförmigen Ablagerung des kohlensauren Kalks, des Quarzsandsteins aus dem Sand zurückführen."

He shows that under non-uniform pressure the solubility (melting) of ice is approximately twelve times greater than under uniform pressure. He also states: "Alle die hier auf das Eis angewendeten Überlegungen gelten für beliebige Stoffe und können zur Erklärung der Erhärtung der Bänke von Steinsalz, Gips, Calciumkarbonat und Thon im Erdboden und unter Abwesenheit jeder Verdampfung herangezogen werden."

Rothmund[32] in a work devoted to solubility relations does not refer to the influence of non-uniform pressure, as neither do Lewis and Randall[33] in a much more recent work, though some slight attention is given to the influence of uniform pressure.

Hildebrand[34] in the most recent work to date on solubility dismisses the subject in five lines only.

This neglect of treatment is merely referred to in order to emphasize how writers of works on physical chemistry ignore matters of considerable geological interest.

Grubenmann and Niggli[35] deal generally with the influence of non-uniform pressure. Following Willard Gibbs, they deduce from considerations of energy, entropy, and unit mass the general relation: ". . . Dem gröszeren Stressdrucke entspricht das grössere Potential, die stärkere Schmelzpunkterniedrung resp. Löslichkeiterhöhung."

[32] V. Rothmund, "Löslichkeit und Löslichkeitbeinflussung," 1907.

[33] G. N. Lewis and M. Randall, "Thermodynamics and the Free Energy of Chemical Substances," 1923.

[34] J. H. Hildebrand, "Solubility," 1924, p. 162.

[35] U. Grubenmann and P. Niggli, "Die Gesteinsmetamorphose," Th. 1, 1924, pp. 167–170.

Nernst[36] considers the effect of non-uniform pressure on vapor pressure following the treatment of Le Chatelier and mentions that the solubility of a solid is increased if, while it is in contact with the solvent, it is compressed by a sieve-like arrangement, a matter that Grubenmann and Niggli also refer to.

As the subject is of geological and metasomatic interest, and in the absence of adequate previous treatment, some detailed attention may be given here to the influence of non-uniform pressure on the solubility of a solid substance in contact with its own aqueous solution.

Two cases must be distinguished:

First Case.—The solid phase and the solution are under the same pressure for a sufficient time to permit equilibrium to be established (*i.e.,* for the solution to become saturated with the solid), after which the solution escapes from the region of uniform pressure, and doing so, being no longer in equilibrium with its surroundings, is supersaturated, consequently deposits its excess of solute and again proceeds to come into equilibrium with its new surroundings. A classical example of this is the weighted wire which slowly imbeds itself in, and cuts through, a block of ice. The same conditions are used to explain, too, the movement of a glacier.

Second Case.—The solid and the solution are at no time under the same pressure. Examples of this would be afforded by a block of material strongly compressed in a vise or press while through a hole in the material water is slowly allowed to flow; or a water jacketed air compressor in which the circulating water in the jacket is not under the same pressure as the air subjected to the compression of the piston.

A homely example of the difference between the two cases is given by considering a man standing firm footed on wet ground covered by a thin layer of running water. The water passing between his instep and the ground represents Case No. 2; while the water trickling or oozing between his soles and heels and the ground represents Case No. 1, either the sole of the boot or the

[36] W. Nernst, "Theoretical Chemistry," translation by L. W. Codd, 1923, p. 766.

ground, or both, being considered as the solid whose solubility is affected.

The mathematical treatment of Case No. 1 is the following:[37]

Consider a system consisting (say) of anhydrous calcium sulphate in contact with its own saturated aqueous solution:

$$\underset{\text{Solid}}{\text{CaSO}_4} \quad \underset{\text{I}}{\qquad} \quad = \quad \underset{\text{Saturated solution}}{\text{CaSO}_4} \quad \underset{\text{II}}{\qquad}$$

Using the notation of Lewis and Randall:

Let F = free energy of the solution containing one mole of $CaSO_4$,

F_1 = free energy content of the solid $CaSO_4$,

$\overline{F}_2$ = partial molal free energy of the $CaSO_4$ in solution,

where $\overline{F}_2 = \dfrac{\partial F}{\partial N_2}$.

Let V = volume of solution containing 1 mole of $CaSO_4$,

V_1 = molal volume of the solid salt,

$\overline{V}_2$ = partial molal volume of the dissolved $CaSO_4$,

where $\overline{V}_2 = \dfrac{\partial V}{\partial N_2}$.

Let N_2 = the mole fraction of the dissolved $CaSO_4$,

a_2 = the activity of the dissolved $CaSO_4$,

γ = the activity coefficient of the dissolved $CaSO_4$,

T { = absolute temperature of the solution, = constant,

P = pressure.

The system being supposed to be at equilibrium, then ΔF = change in free energy attending a change in state,

$$= \overline{F}_2 - F_1 = 0.$$

$$\partial F_1 = \partial \overline{F}_2,$$

$$\partial F_1 = V_1 dp, \qquad \partial \overline{F}_2 = \overline{V}_2 dp + \left(\frac{\partial \overline{F}_2}{\partial N_2}\right) dN_2,$$

[37] In what immediately follows I have had the kind assistance of Dr. R. H. Gerke, of the Department of Physical Chemistry, Mass. Inst. Technology.

since

$$\partial F_1 = \partial \overline{F}_2,$$

$$V_1 dp = \overline{V}_2 dp + \left(\frac{\partial \overline{F}_2}{\partial N_2}\right) dN_2,$$

and since

$$\partial \overline{F}_2 = RT ln a_2,$$

$$V_1 dp - \overline{V}_2 dp = \left(\frac{\partial \overline{F}_2}{\partial N_2}\right) dN_2$$

$$= RT \left(\frac{\partial ln a_2}{\partial N_2}\right) dN_2,$$

$$\frac{dp}{dN_2} = RT \frac{\left(\frac{\partial ln a_2}{\partial N_2}\right)}{(V_1 - \overline{V}_2)},$$

$$\int dN_2 = \int \frac{(V_1 - \overline{V}_2)}{RT\left(\frac{\partial ln a_2}{\partial N_2}\right)} dp,$$

$$N \Bigg]_{\substack{N \text{ saturated solution} \\ \text{at 1 atmos.}}}^{\substack{N_x \text{ moles saturated} \\ \text{solution at } x \text{ atmos.}}} = \left[\left(\frac{V_1 - \overline{V}_2}{RT\left(\frac{\partial ln a_2}{\partial N_2}\right)}\right) P\right]_{P=1 \text{ atm.}}^{P=x \text{ atm.}}$$

Since V_1 may be $>$ or $< V_2$, the solubility may be increased or decreased by non-uniform pressure, though in the great majority of cases the effect is an increase.

The integration of the term

$$\frac{(V_1 - \overline{V}_2)}{RT\left(\frac{\partial ln a_2}{\partial N_2}\right)}$$

involves the investigation of available data from different sources, a lengthy and laborious piece of work that the writer was unable to undertake, and which may be left to the painstaking attention of someone else.

Assuming

$$\frac{(V_1 - \overline{V}_2)}{\left(RT \frac{\partial ln a_2}{\partial N_2}\right)}$$

to be constant (through the range of pressure involved) = K. The relation reduces to the form

$$N_{\substack{x \text{ moles saturated} \\ \text{solution at } x \text{ atmos.}}} - N_{\substack{\text{saturated solution} \\ \text{at 1 atmos.}}} = K(P_{x \text{ atmos.}} - P_{1 \text{ atmos.}})$$

And as a first approximation

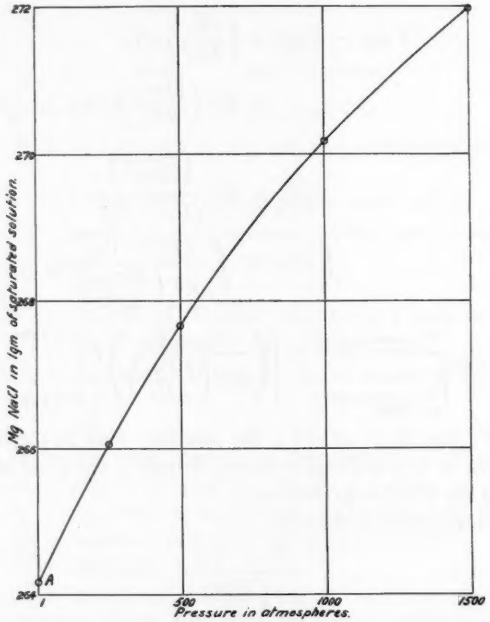

FIG. 1. Effect of uniform (volume) pressure on the solubility in water of NaCl at 24.05°. From data given by Cohen and Schut. The approximate relation solubility $\propto$ pressure for non-uniform (linear) pressure would be represented by a tangent to the curve at A.

$$\text{Solubility} \propto \text{Pressure}$$

except in the few cases where $\overline{V}_2 > V_1$.

The error involved by assuming

$$\frac{(V_1 - \overline{V}_2)}{RT\left(\frac{\partial ln a_2}{\partial N_2}\right)}$$

to be constant through the entire range of pressure is small when the pressure is moderate, but increases with increase of pressure. It is equivalent to omitting p^2 in Cohen and Schut's[38] equation

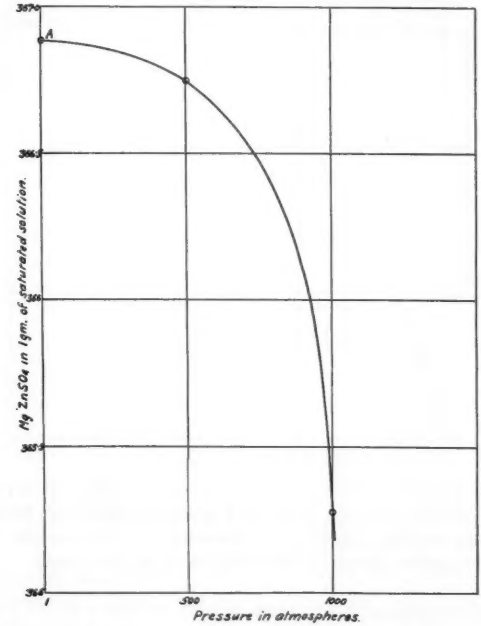

FIG. 2. Effect of uniform (volume) pressure on the solubility in water of $ZnSO_4$, H_2O at 25°. From data given by Cohen and Schut. The approximate relation solubility $\propto$ pressure for non-uniform (linear) pressure would be represented by a tangent to the curve at A.

$$L = A + bp - cP^2,$$

where L = solubility, p = pressure in atmospheres,
c = constant of the second order of smallness.

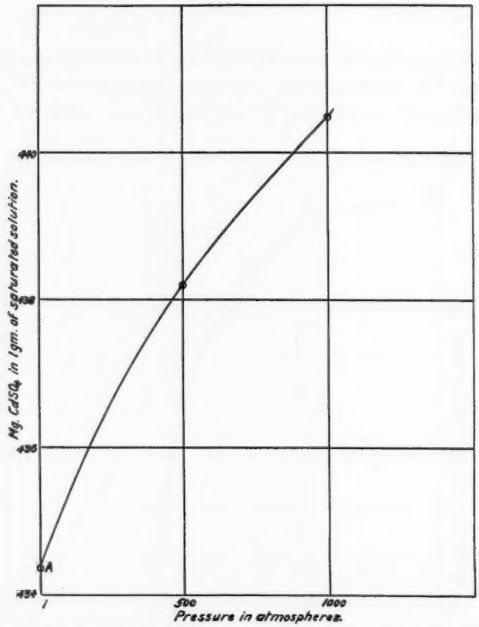

FIG. 3. Effect of uniform (volume) pressure on the solubility in water of $CdSO_4$ $8/3H_2O$ at 25°. From data given by Cohen and Schut. The approximate relation solubility $\propto$ pressure for non-uniform (linear) pressure would be represented by a tangent to the curve at A.

The divergence of the term

$$\frac{(V_1 - \overline{V}_2)}{RT\left(\frac{\partial ln a_2}{\partial N_2}\right)}$$

[38] E. Cohen and W. Schutt, *op. cit.*, p. 386.

from constancy is shown graphically, in Figs. 1–3, in the case of sodium chloride, zinc sulphate, and cadmium sulphate by plotting Cohen and Schut's data for those substances.

The treatment of Case 2 is the following:

Using the same system and the same notation as in Case 1 and giving the symbols the same significance.

$$\partial F_1 = V_1 dp,$$

$$\partial \overline{F}_2 = \overline{V}_2 dp + \left(\frac{\partial \overline{F}_2}{\partial N_2}\right) dN_2.$$

But since the solution undergoes no change in pressure

$$dp = 0.$$

Hence

$$\partial \overline{F}_2 = \left(\frac{\partial \overline{F}_2}{\partial N_2}\right) dN_2$$

since

$$\partial F_1 = \partial \overline{F}_2,$$

$$V_1 dp = \left(\frac{\partial \overline{F}_2}{\partial N_2}\right) dN_2;$$

$$\therefore \quad \frac{dN_2}{dp} = \frac{V_1}{\left(\frac{\partial \overline{F}_2}{\partial N_2}\right)} = \frac{V_1}{RT\left(\frac{\partial ln a_2}{\partial N_2}\right)}$$

since $\partial \overline{F}_2 = RT ln a_2$

$$\int dN_2 = \int \left(\frac{V_1}{RT\left(\frac{\partial ln a_2}{\partial N_2}\right)}\right) dp$$

$$N \Big]_{\substack{N = x \text{ moles saturated solution at } x \text{ atmos.} \\ N \text{ saturated solution at 1 atmos.}}} = \left[\left(\frac{V_1}{RT\left(\frac{\partial ln a_2}{\partial N_2}\right)}\right) P\right]_{p=1 \text{ atm.}}^{p=x \text{ atm.}}$$

Since V_1 is positive, in this case *the solubility is always increased by pressure.*

Assuming

$$\frac{V_1}{RT\left(\frac{\partial ln a_2}{\partial N_2}\right)}$$

to be constant through the range of pressure and $= K$

$$N_{\substack{x \text{ moles saturated} \\ \text{solution at } x \text{ atmos.}}} - N_{\substack{\text{saturated solution} \\ \text{at 1 atmos.}}} = K^k(P_{x \text{ atmos.}} - P_{1 \text{ atmos.}})$$

and as a first approximation.

In this case

$$\text{Solubility} \propto \text{pressure always.}$$

The conditions referred to by Nernst,[39] ". . . the solubility of solid is increased if whilst it is in contact with the solvent it is compressed by a sieve-like arrangement," and those of Grubenmann and Niggli[40] indicated in the following words: ". . . Betrachten wir den relativ idealen Fall; den man sich unter Zuhilfenahme eines für die Flüssigkeit durchlässigen Druckstempels (ohne Ausweichungsmöglichkeit für die feste Phase) verwirklicht denken kann," are included under Case 2 just considered.

Since the conditions of metasomatism have been accepted as being isothermal, T has been taken as constant in the foregoing treatment. If T is variable, entropy has to be taken into account and the relations become more complicated.

After having thus considered the possible means of relief from the " force of growing crystals," supposing such to be involved in vein formation, let us return to specific metasomatism and the relations of palasome to metasome and vice versa.

According to Case 1 of solubility changes, the escaping solution, when no longer under the higher pressure and consequently not in equilibrium with the surroundings, deposits excess of solute. This deposition, if continued, must ultimately close the openings or channels required for metasomatic transportation and thus the process will automatically cease. The effect of non-uniform pressure, therefore, on solubility is essentially a consolidating and cementing one, and it is in this light that Le Chatelier used it geologically. It affords also a basis for Van Hise's zone of cementation, though not specifically referred to by that authority.

[39] W. Nernst, *op. cit.*

[40] U. Grubenmann and P. Niggli, *op. cit.*, p. 168.

Grubenmann and Niggli[41] refer to this "Wiederabsatz" and see in it with constant intensity and direction of stress ". . . eine ständige Umlagerung der Materie, die schlieszlich zu einer gerichteten Textur, der Kristallisationsschieferung, führen kann."

If it be urged that a bed of gypsum (say) at its contact with overlying strata (*i.e.*, on the hanging wall contact or roof) presents a surface containing a very large number of crystal points, each one of which may be considered to exert non-uniform pressure on the roof in the presence of solution, it is easy to see that the process of solution induced by the pressure of the points will go on accompanied by deposition till the inequalities and openings cease to exist and a surface be produced that will exert uniform pressure on the roof or hanging wall. Conditions generally will then approximate to those of the hydrostatic pressure exerted by an intruding sill, with the disadvantage in the case of the gypsum bed that material is *not* (and can not be through lack of the necessary openings) continuously fed to it as in the case of the sill. Hence the gypsum bed *can not* increase in thickness and lift or otherwise displace its hanging wall.

There are, therefore, opposed to the theory of vein formation by the direct action of the force (linear) of crystallization a number of weighty considerations.

Consecutively, in the order in which they have been dealt with in the foregoing, these are:

1. Those based on Le Chatelier's theorem and exemplified by the effect of pressure on ice.
2. The difficulties involved in supplying the growing crystals, under the existent geological conditions, with the necessary supersaturated solution.
3. The limitations imposed by the effect of pressure on the melting point of substances.
4. The limitations connected with the influence of pressure on the solubility of substances. These were foreseen by Becker and Day, but have been overlooked by the advocates of the theory.

[41] U. Grubenmann and P. Niggli, *op. cit.*, p. 170.

5. The cementing and closing effects of the deposition resulting from increase of solubility due to non-uniform pressure and the consequent loss of entrance and exit openings for the metasomatic solutions.

The present writer submits that these considerations dispose generally of Case 3 of the possible metasomatic relation of palasome to metasome and of the force of growing crystals as an important factor in vein formation, in particular.

There remain Cases 1 and 2, of which 1 has been seen to be excluded by microscopic evidence. It, therefore, appears that Case 2, in which the metasome exactly fills the space previously occupied by the palasome, is the only occurring one under pressure conditions.

What, then, is the method by which the palasome is actually removed? Is it by solution, by chemical decomposition, or by both? Taber[42] considers that one mineral may take the place of another in at least three different ways:

(1) By solution of the original mineral and subsequent deposition in the space vacated; (2) by solution of the original mineral and simultaneous deposition of the replacing mineral without chemical reaction between them; (3) by a chemical reaction involving the addition, subtraction, or interchange of one or more elements.

He rules out 1 on microscopic evidence and concludes apparently that both (2) and (3) are operative.

W. H. Emmons[43] considers that "metasomatism takes place by solution and reprecipitation in very small openings." He refers to the possibility of solution cavities being formed, but states that ". . . In metasomatic replacement reprecipitation generally succeeds solution so closely that they seem to be essentially parts of a single process."

Lindgren[44] has defined metasomatism as ". . . the process of

[42] S. Taber, "Mechanics of Vein Formation," *Trans. Am. Inst. Min. Eng.*, vol. 51, 1915.

[43] W. H. Emmons, "Principles of Economic Geology," 1918, pp. 218–219.

[44] W. Lindgren, "Mineral Deposits," 1919, p. 69.

practically simultaneous capillary solution and deposition by which a new mineral of partly or wholly differing chemical composition may grow in the body of an old mineral or mineral aggregate." A more recent definition[45] of his states: "I would define metasomatism as an essentially simultaneous process of solution and deposition by which, in the presence of a fluid phase one mineral is changed to another of differing chemical composition."

The phenomena of metasomatism may be examined under the two aspects of:

A. Removal of the palasome by solution without chemical change.

B. Removal of the palasome by solution accompanied by chemical change.

While these may not provide for all the cases occurring in nature, they certainly cover by far the greater number.

A. By Solution and Without Chemical Change.—The effect of uniform (volume) pressure on a system in equilibrium is to increase the solubility of substances whose solution is attended by decrease of total volume and decrease the solubility of those going into solution with increase of total volume.

Let A = palasome. B = metasome,
V_{A_s} = specific volume of A in the solid state,
V_{Al}[46] = volume of unit weight of A in solution,
V_{B_s} = specific volume of B in the solid state,
V_{Bl} = volume of unit weight of B in solution.

Then under pressure the condition for B to metasomatically displace A or for

$$A_{\text{solid}} \longrightarrow A_{\text{liquid}}$$

and simultaneously

$$B_{\text{liquid}} \longrightarrow B_{\text{solid}}$$

[45] W. Lindgren, Presidential Address, Geological Society of America, Dec., 1924.

[46] More rigorously the molal volume of A and B in the solid state and their partial molal volumes in solution should be taken, but this omission does not invalidate the accuracy of the reasoning given.

is that

$$(V_{A_s} - V_{Al}) > (V_{Bl} - V_{B_s}).$$

More specifically if A = palasome and B = metasome,
Δx[47] = change in volume attending solution of A.
Δy = change in volume attending solution of B.

Case 1.—If both A and B go into solution with decrease of total volume, then both Δx and Δy are negative.

$$A_{\text{solid}} \longrightarrow A_{\text{liquid}} = -\Delta x,$$
$$B_{\text{liquid}} \longrightarrow B_{\text{solid}} = +\Delta y.$$

The condition for this replacement to proceed under pressure is that $(\Delta x - \Delta y)$ is negative.

Case 2.—If both A and B go into solution with increase of total volume, then Δx and Δy are both positive.

$$A_{\text{solid}} \longrightarrow A_{\text{liquid}} = +\Delta x,$$
$$B_{\text{liquid}} \longrightarrow B_{\text{solid}} = -\Delta y.$$

The condition for this to proceed under pressure is that $(\Delta y - \Delta x)$ is negative.

Case 3.—A goes into solution with *decrease* of total volume, B with *increase*.

$$A_{\text{solid}} \longrightarrow A_{\text{liquid}} = -\Delta x,$$
$$B_{\text{liquid}} \longrightarrow B_{\text{solid}} = -\Delta y.$$

The condition that there be a decrease in total volume is fulfilled in this case both in the disappearance of the palasome and the appearance of the metasome, hence this is the most favorable combination of volume conditions for metasomatic replacement under pressure.

[47] With more mathematical rigor

Δx and Δy should be so taken that
$\Delta x = \text{Vol}_{A_{\text{liquid}}} - \text{Vol}_{A_{\text{solid}}} = \text{increase},$
$\Delta y = \text{Vol}_{B_{\text{solid}}} - \text{Vol}_{B_{\text{liquid}}} = \text{increase}.$

Then net change in volume $= \Delta x + \Delta y =$ decrease if the reaction is to proceed under pressure.

Case 4.—*A* goes into solution with *increase* of total volume, *B* with *decrease*. Then Δx is positive, Δy is negative.

$$A_{\text{solid}} \longrightarrow A_{\text{liquid}} = +\Delta x,$$
$$B_{\text{liquid}} \longrightarrow B_{\text{solid}} = +\Delta y.$$

Since there is an increase in total volume attendant on both the displacement of the host and the installation of *B*, this combination of volume relations inhibits metasomatic replacement under pressure unless the force of crystallization is exerted.

The actual solution proceeds, so far as we know at present, from openings of super-capillary, capillary, and sub-capillary size. An important feature connected with this is that the surface of the palasome from which solution takes place is very large for a given volume of solution. Since rate of solution is proportional to the surface exposed and to the difference between the solubility of the palasome and its concentration in the solution, it follows that saturation will be rapidly reached in the thin layers or films of solution involved, for Nernst[48] has shown ". . . it is highly probable that at every boundary between two phases equilibrium is established with a practically infinite velocity (*i.e.*, compared with the rate of diffusion)."

While actual solution is thus almost certainly rapid, the removal of the material in the saturated solutions from the site of metasomatism must, from the nature of the case, be slow. The subject of metasomatic diffusion can not be gone into here. It has quite recently been dealt with elsewhere.[49] It must be admitted, however, that our present knowledge on the subject is very deficient.

B. Removal of the Palasome by Solution Accompanied by Chemical Change.—In considering this it seems useful, first of all, again to emphasize the essential difference between the conditions of chemical change involved in metasomatism and those of the laboratory, yet it is with purely the latter class of reactions that

[48] W. Nernst, "Theoretical Chemistry," translated by L. W. Codd, revised in accordance with eight-tenth German edition, 1923, p. 670.

[49] H. C. Boydell, *Bull. Inst. of Min. and Met.* (London), Dec. 1924, pp. 83–93.

metasomatic and geological processes generally are compared. In the great majority of laboratory reactions surface does not play an important part (though in catalysis its influence is important and fully recognized by chemists), yet in metasomatism surface is always important, reactions have to be thought of almost as if they took place in two rather than in three dimensional space, and catalysis probably is of general occurrence. This is a matter that is generally overlooked and the only case of a chemist who has commented on the subject is, as pointed out by Lindgren,[50] that of Sosman,[51] who wrote ". . . the flow of liquids is evidently accompanied by phenomena not clearly understood. It is very probable that some of the phenomena of replacement are of this class and are not reactions which can be represented by the familiar balanced equations of chemistry."

The chemical investigation of metasomatism will make more progress when chemists generally take the same viewpoint.

The reactions of metasomatism then take place in thin films, the generalization of Nernst, previously referred to, holds, and equilibrium is rapidly established. This being the case, it is ingress and egress of solutions to and from the site of displacement of the palasome which apply the brake to metasomatic replacement.

With regard to the type of chemical process involved in metasomatism, double decomposition is probably the most important. Adsorption, followed or not by chemical union, is no doubt operative and offers an explanation of the origin of minerals of variable composition such as tourmaline, the sulpharsenides and sulphantimonides, etc. (not forgetting, of course, the large number of such minerals which occur in the zone of oxidation or the shallow zone). Adsorption may also account for the small varying amounts of seemingly adventitious elements in such minerals as apatite, tourmaline, tetrahedrite, etc.

Since adsorption takes place at surfaces, it follows that material with large surface development favors adsorption. Now gels

[50] W. Lindgren, Presidential Address, 1924.

[51] R. B. Sosman, *Bull. Geol. Soc. Am.*, vol. 35, 1923, p. 125.

and gelatinous precipitates have large surface and are active adsorbents. May it be argued from this that variability of composition is indicative of origin (partly at least) by adsorption and therefore indicates possible colloidal origin? May this be used as a *tentative* criterion of colloidal origin for a mineral?

This prompts the question, Do minerals of variable composition show the usual criteria of colloidal origin such as colloform structures, etc.? Rogers'[52] lucid review of the amorphous minerals shows that this is so in many cases, though, be it stated, he confines his attention chiefly to minerals occurring in the zone of oxidation. Lindgren[53] also refers to this variation of composition in colloidal minerals.

Whatever may be the types of chemical process involved in metasomatism, let it be again emphasized that they take place in films and not in even *comparatively* large open spaces or large volumes of solution.

Another point to which attention may be called, and which has been referred to elsewhere,[54] is that the metasomatic solutions given entrance in the form of a crack or some minute opening are never under the necessity of actually permeating the substance of the palasome. Along the crack the latter is removed and the metasome deposited. Metasomatism proceeds outward from the crack by fresh supplies of reacting solution, passing to "the front" or line of attack on the host through the mass of the recently deposited metasome which may well be comparatively more or less open in texture. Irving[55] has drawn attention to this matter and urged that the advancing solutions in replacement (metasomatism) must have found their way constantly through the newly formed ore, which is generally porous.

Liesegang[56] has referred to the same thing and emphasized the point that flow or diffusion always takes place, not through the

[52] A. F. Rogers, *Jour. of Geol.*, 25, 1917, pp. 514–541.
[53] W. Lindgren, "Colloidal Behaviour" (Bogue), 1924, vol. II., p. 447.
[54] H. C. Boydell, *op. cit.*, p. 85.
[55] J. D. Irving, ECONOMIC GEOLOGY, 6, 1911, p. 558.
[56] R. E. Liesegang, "Geologische Diffusionen," 1913, p. 15.

homogeneous unaltered palasome, but through the porous mass of the deposited metasome.

Now as to the nature of the metasomatic solutions, are they molecular or colloidal ones? What is the degree of dispersion of the solute or solutes they contain? The means by which molecular solutions reach the site of metasomatism requires no special attention here, but in the case of colloidal solutions some limitations are imposed that call for consideration. With transportation by flowage of the solution, the ability of colloidal particles to be transported in this way will evidently depend on the ratio of their diameter to the width of the openings through which flowage takes place. The size of colloidal particles, though, is not necessarily a bar to the transportation or movement of the material that compose them. Silica, in the present state of our knowledge, is always carried in colloidal solution, yet as Hatschek[57] has pointed out: ". . . Many plants had a coating of silica, among them species which grew in a few days, such as the fertile stems of equisetum. If silicic acid were present in the soil liquid in colloidal solution, it could not pass through the cell membranes—while if it was in true solution, it was difficult to account for the quantities taken up in a short time from a very small volume of soil. An even more mysterious case were the siliceous sponge spicules: he had been told by zoölogical friends that specimens 5/8 inch thick and 2 feet long were known. The suggestion that the organisms took up, and decomposed, silicates was obvious, but did not help much, as silicates in the likely concentrations would be completely hydrolyzed." It certainly appears as if some organisms have the power of taking colloidal silica from solution and increasing its dispersion to a degree sufficient to permit of its entrance into their tissues. Where movement is by diffusion, it must be remembered that the rate of diffusion of colloid particles is very slow, but, though slow, diffusion takes place and its rate increases as the size of the particles decrease and more nearly approach those of molecular solutions. It is for this reason that some gold sols diffuse comparatively rapidly.

[57] E. Hatschek, *Bull. Inst. Min. and Met.* (London), February, 1924, p. 13.

Generally speaking, it would seem that in more highly dispersed colloidal solutions, and with the factor of geological time taken into consideration, colloidal material can, in the larger openings at any rate, be transported to and from the site of metasomatic action, though not with the same facility or degree of availability in pores and open spaces of small size as molecularly dispersed material.

Given access of colloidal material to the site of metasomatism, its precipitation may be effected by either chemical or physical means, and so it can play the part of metasome; in this case its large specific surface fits it particularly well for the rôle of adsorbent in subsequent adsorption processes.

In addition to what is transported, locally produced, or authigenous, colloidal material may, and no doubt does, play a part in metasomatism. All silicates, sulphides, and carbonates may be regarded as the salts of "weak" acids (and in most cases, too, of "weak" bases), and in consequence as having a strong tendency to undergo hydrolysis in solution. The conditions of metasomatism are not inhibitory of this, but rather, on the other hand, on account of the surface development would favor it. Hydrolysis of silicates, sulphides, and carbonates commonly produces colloidal material and such products may be deposited locally or be removed in solution according to conditions, such as the presence of a precipitant, peptizer, a protecting agent or solvent, etc.

Deposition from colloidal solutions may result in the formation of:

(1) A gelatinous precipitate, or
(2) A gel.

A gelatinous precipitate must not be confused with a so-called "colloidal precipitate." The latter is non-settling and has little or no tendency to form an agglomerate—*i.e.*, to coagulate. A gelatinous precipitate, on the other hand, is an agglomerate and is viscous. Bancroft[58] deals with this matter and says that a gelatinous precipitate apparently always results when a slightly

[58] W. D. Bancroft, "Applied Colloid Chemistry," 1921, p. 163.

soluble salt is precipitated from very concentrated solutions. The difference between a gel and a gelatinous precipitate, on the other hand, is that with the gel there is a much closer association of the dispersion medium and the disperse phase than there is with a gelatinous precipitate, to the extent that the liquid phase is visible with a gelatinous precipitate, while with a gel it is not. To the naked eye the gel looks like a homogenous mass, while with a gelatinous precipitate two phases are visible. Examples of gelatinous precipitates are ferric, chromic, and aluminum hydroxides, also zinc sulphide, etc.

A metasome formed of gelatinous precipitate will only differ in the matter of larger specific surface, more finely crystalline (possibly amorphous) texture, tendency to desiccation, and porosity from one formed by an originally crystalloidal precipitate.

Gels may be produced from either concentrated or dilute solutions. Their production from concentrated solutions has been investigated by Von Weimarn and others, who have found the necessary condition to be a high degree of supersaturation prior to precipitation or coagulation.

The question arises as to whether the necessary high degree of supersaturation for this method of gel formation is attained under the conditions previously specified and considered in this paper. Now Noyes and Whitney[59] have assumed that at the boundary between solid phase and solution the latter is always saturated. Since in metasomatism the film of solution will usually be very thin, and, moreover, will have *two* boundaries in contact with the solid (if the latter be homogeneous), it follows that the portion of the film which is saturated will bear a very large proportion to the volume of the film. In addition, diffusion within the small width of the film will be able to distribute the solute uniformly, hence the whole of the film may be considered to be saturated. But saturation is not supersaturation, and since that state is essential to the method of gel formation considered at the moment, there remains to be investigated how supersaturation can arise in metasomatism.

[59] A. A. Noyes and W. R. Whitney, *Zeitschr. f. physik. Chem.*, 23, 1897, pp. 689–692.

While contact of *supersaturated* solution with a crystal is considered necessary for the exertion of the force of crystallization, it is strange that the question of how supersaturated solution may be produced under geological conditions has not been given attention by the advocates of the theory of "the force of growing crystals." The usual method of formation by cooling a saturated solution is not likely to be reproduced under metasomatic conditions.

Thomson[60] has calculated that the effect of surface tension in small pores increases solubility to a considerable extent.[61] According to him, the solubility of potassium sulphate in water contained in the pores of such a substance as meerschaum or graphite, assuming the pores of such to have a diameter of 20 $\mu\mu$ (.00002 mm.), is increased by surface tension to the extent of nearly 25 per cent. at a temperature of 27° C. The same authority states that salts generally which raise the surface tension of water (*i.e.*, are negatively adsorbed) have their solubility increased when they are contained in spaces of capillary dimensions. These solutions in pores would be in equilibrium with their surroundings, but if displaced by any cause from the pores, they would be supersaturated with regard to other surroundings and eminently suited for the production of gels by subsequent precipitation.

Another possible method by which supersaturated solutions might be formed is by the introduction into a solution of a second solute exercising either a "common ion" or a salting-out effect on an original solute. Continuously, this can be conceived of as being done in metasomatism by the meeting of two solutions transported along different openings. Taber[62] would seem to have utilized a method of producing supersaturation analogous to

[60] J. J. Thomson, "Applications of Dynamics to Physics and Chemistry," 1888, p. 255.

[61] Taber (apparently without knowledge of Thomson's work) has assumed this increase of solubility in connection with his experiments, for he writes (*Proc. Nat. Acad. Sciences*, 3, 1917, p. 300): ". . . Crystallization is retarded or prevented in supersaturated solutions which occupy small capillary or subcapillary spaces; therefore crystals may be supplied with material for growth by diffusion through solutions occupying such spaces. . . . "

[62] S. Taber, *Mining and Scientific Press*, 116, 1918, p. 128.

this, for he claims ". . . mingling of two solutions differing in composition" to have been one of the means by which he investigated the conditions under which growing crystals may exert pressure against other solid bodies. For deposition of material deposited by relief of the supersaturation to be confined to the faces of the growing crystal and not to result in the formation of other nuclei followed by crystallization round these, as is usual, would require extremely slow mixing of the different solutions. Freundlich[63] in his consideration of the rate of crystallization in supersaturated solutions expressly excludes the case of the formation of new crystals around new nuclei.

The conditions for the formation of large crystals by diffusion processes have been investigated by Johnston,[64] who states ". . . the formation of large particles of slightly soluble substances, therefore, is favored: (1) by causing the separation of the substance to proceed very slowly; (2) by so choosing the temperature and composition of the medium as to have the substance as soluble as possible." While the attainment of the first condition would be likely in metasomatism, that of the second would be purely adventitious. Johnston's attempts to form crystals of silicates by diffusion processes resulted in the separation of *colloidal material only*. He considers this may have been due ". . . to hydrolysis, or to the insolubility of the silicate, or to both of these factors." Johnston's experiments were carried out in open vessels, with no foreign substance present other than a layer of paraffin wax at the surface to prevent evaporation. Hostetter[65] has more recently described a more complicated apparatus for the growth of large and perfectly developed crystals. Under metasomatic conditions, one would be inclined to think that, owing to the large surface of palasome exposed to the solutions, the tendency would be for the formation of a finely divided precipitate and for Johnston's ideal conditions not to be realized. Mere exposure of the surface of a foreign substance to the solutions would not, however, seem to inhibit the formation of large crys-

[63] H. Freundlich, "Kapillarchemie," 1923, p. 457.

[64] John Johnston, *Jour. Am. Chem. Soc.*, 36, 1914, pp. 16–19.

[65] J. C. Hostetter, *Journ. Wash. Acad. Sciences*, 9, 1919, pp. 85–94.

tals by diffusion processes, for Hatschek and Simon[66] produced comparatively large gold crystals in a silica gel by diffusion. The experimental work of Daubrée, Dreaper, and Johnston shows the great tendency there is for all openings to become closed by deposition from solution in such experiments, a condition that may or may not exist in metasomatism according to the factors involved.

Still another conceivable method applying to colloidal solutions (sols) is the exertion on the disperse phase of *protective action* by which means the concentration of the disperse phase is increased and a state akin to supersaturation is produced. Many organic protecting agents are known (it is *not* suggested that they occur in metasomatism), and Bastin[67] has shown that colloidal silica acts as a protecting agent to gold and silver in solution. When the amount of the disperse phase exceeds the power of the "protecting agent" to keep it in solution, precipitation follows. Bancroft[68] gives a good example of this; hydrous chromic oxide peptized by caustic potash prevents the precipitation of ferric hydrate, but if the latter be present in too great amount, it is precipitated and carries down the chromic oxide, too. According to Freundlich,[69] strong adsorption of an impurity on a crystal may prevent crystallization even in a supersaturated solution. In this way it is conceivable that an increased degree of supersaturation might be caused that would later find relief.

Still another means by which supersaturation (or the colloidal conditions corresponding to it) might be produced is by peptization, as was effected in the case of sulphides by Tolman and Clark,[70] and also by Clark and Menaul,[71] who peptized metallic sulphides by means of hydrogen sulphide. On the removal of the peptizer precipitation follows. If the solution of calcium car-

[66] E. Hatschek and R. L. Simon, *Trans. Inst. Min. and Met.* (London), 21, 1912, pp. 451–480.

[67] E. S. Bastin, *Wash. Acad. Sci.*, February 4, 1915.

[68] W. D. Bancroft, *op. cit.*, p. 170.

[69] H. Freundlich, "The Elements of Colloid Chemistry," 1924, translation by G. Barger, p. 101.

[70] C. F. Tolman and J. D. Clark, ECON. GEOL., 9, 1914, pp. 559–592.

[71] J. D. Clark and P. R. Menaul, ECON. GEOL., 11, 1916, pp. 37–41.

bonate by means of carbon dioxide in aqueous solution be regarded as peptization, it is probable that under pressure supersaturated solutions of calcium carbonate would be produced that would yield a gel on removal of the "peptizer."

Finally there is the possibility of the presence in metasomatism of some inorganic substance (at present unknown) having the power of facilitating supersaturation in the same way that methyl alcohol does. The discovery of such an inorganic substance of common geological occurrence would render certain the colloidal occurrence and transport of substances that at present only have suspected colloidal existence.

Given the foregoing possible methods by which supersaturated solutions might be formed during metasomatism, it can not be said that their actual occurrence would help the advocates of the "force of growing crystals"—theory of vein formation. The onus certainly rests on them to show that deposition from such supersaturated solutions would not be rapid, accompanied by the formation of numerous nuclei, and therefore of the nature of ordinary precipitation rather than the slow deposition or withdrawal from solution required for the uniform growth of preexisting crystals.

The production of gels from *dilute* solutions or sols is an idea of recent growth and is due chiefly to Weiser,[72] whose views have been summarized elsewhere[73] in the following terms: ". . . Weiser has quite recently pointed out that this is not the usual condition of gel formation, and that the most stable gels are relatively dilute and are prepared by *slow* precipitation of dilute colloids or on mixing of dilute solutions where the degree of supersaturation is only small. The same writer considers that since finely divided particles that adsorb water strongly are essential in gel formation, the best method is the precipitation of a hydrous substance from colloidal solution, and he has prepared a number of inorganic gels in this way (among them a firm one of chromic oxide containing 0.19 per cent. Cr_2O_3).

[72] H. B. Weiser, Colloid Symposium monograph, Univ. of Wisconsin Chem. Dept., 1923, pp. 38–61; also 'Colloid Behavior" (by Bogue), vol. I., pp. 393–394.

[73] H. C. Boydell, *op. cit.*, p. 13.

"He also refers to the importance of the *time element* and thinks that many more substances would form gels *if given longer time* (the latter condition in particular will appeal to geologists who always have the enormous reservoir of geological time to draw from). These conditions, on the whole, are more likely than Von Weimarn's of reproduction in Nature and their existence renders the formation of gels under geological conditions more probable and also easier of application."

This certainly applies to metasomatic conditions. By the occurrence of quite usual ones, gels may be easily conceived of as resulting during the displacement of palasome by metasome under the influence of solutions likely to be existent in, and during the long time usually available for and believed to be required by, metasomatism.

Considerations such as the foregoing have led Lindgren[74] to advocate "Gel-metasomatism or replacement of crystalloids by gels." This, of course is not the first application of colloidal processes to geological phenomena, for Breithaupt more than a century ago examined what he called porodine substances which correspond to present-day colloids. Cornu[75] was an indefatigable worker in this line during his brilliant and all too short career. Marc and Himmelbauer[76] have ably discussed the subject. Scott[77] has collected and admirably summarized the very extensive and equally scattered literature and geologists are under a distinct obligation to him on that account. Hubbard[78] has interestingly reviewed the subject, quite recently Lindgren[79] has treated it from the viewpoint of colloid minerals and ore deposits, and Boydell[80] has discussed at length the influence of colloidal

[74] W. Lindgren, Presidential Address, Geol. Soc. of Am., Dec. 1924.

[75] F. Cornu, volumes of Koll. Zeitschr., 1–5, from 1905–1910.

[76] R. Marc and A. Himmelbauer, "Fortschritte Mineral Krist u. Petrog.," 3, 1913, p. 33.

[77] A. Scott, "The Application of Colloid Chemistry to Mineralogy and Petrology," 1921, British Assoc. Adv. Sci. Fourth Report on Colloid Chemistry, pp. 204–243.

[78] G. D. Hubbard, *Am. Jour. Sci.*, 5–4, 1922, pp. 95–110.

[79] W. Lindgren, "Colloid Behavior," (By Bogue) 1924, pp. 445–465.

[80] H. C. Boydell, "The Rôle of Colloidal Solutions in the Formation of Mineral Deposits," *Bull. Inst. Min. and Met.* (London), Dec. 1924.

solutions in mineral deposits. There has thus, and with the assistance of other workers too numerous to mention, grown up an astonishingly extensive, varied, and very scattered literature on the general subject, but in spite of this Lindgren was the first to envisage the part played by the colloidal state in the widely prevalent geological process of metasomatism.

The foregoing having been quite general, let us take as an example of metasomatism an aggregate of quartz, sericite, and calcite replacing labradorite as a palasome, a case which, though assumed here for the purpose of illustration, is of frequent geologic occurrence. Assuming the necessary openings for the ingress of solution, let it be supposed that the latter contains carbonic acid and potassium ions together with possibly other substances, which, however, do not influence the metasomatic phenomena.

On contact with the labradorite the tendency will be for sufficient of that substance to establish equilibrium (at the temperature involved) to go into solution. Simultaneously with solution hydrolysis of the very slightly soluble silicate will take place with the formation and deposition of gelatinous alumina and silica, together with calcium carbonate, which may or may not be gelatinous, too. If the concentration of the carbonic acid in the invading solution be sufficiently high, some or all of the calcium carbonate will "dissolve" and pass away by diffusion. In this case let it be supposed that the calcium carbonate does not so "dissolve." Since the silica and alumina are capable of becoming associated with the varying amounts of water on passing into the colloidal state, there will be no definite stoichiometric volume limitations imposed on the replacing alumina, and silica gel other than it can not do more than fill the space previously occupied by the portion of the palasome that went into solution.

Some of the potassium will be adsorbed on the large surface exposed by the silica and possibly on the alumina as well. The results of soil investigations provide ample justification for this assumption. The process will go on so long as the necessary solution invades the labradorite palasome or, in a more restricted

way, as will be described later, so long as moisture is present, it being presumed, of course, that other conditions remain substantially the same. Thus the limit is the complete removal of the labradorite and its metasomatic replacement by a gelatinous mass of alumina, silica together with their associated water and adsorbed potassium and either crystalline or gelatinous calcium carbonate.

In the course of time all the alumina together with potassium and silica in the necessary amounts will combine to form sericite, using up associated water in doing so.[81]

The calcium carbonate, owing to its strong crystallizing tendency, may be easily thought of as passing either into the crystalline state or, if it were so when originally deposited, of becoming more coarsely crystalline by the well-recognized process of larger crystals developing at the expense of smaller ones. The surrounding rock may or may not exercise some pressure on the originally gelatinous mass of metasome and thus express that portion of the associated water which can not be retained in the resulting mass of metasome.

Syneresis and crystallization, however, are the more likely processes by which excess of water is eliminated from the gelatinous material. In this connection it is to be remembered that sericite contains 4.5 per cent. of water and opal[82] from 3 per cent. to 13 per cent.

There would thus be formed the felted aggregate of silica, calcite, and sericite so familiar under the highest powers of the microscope as the resultant product of the metasomatism of the calcic felspars.

The original gel condition from which our sericite has been formed, according to the process just outlined, is eminently suited for the production of the fibrous, sheafy form of that mineral as seen in thin sections of altered rocks. Any pores inherited from the original gel condition would be ultramicroscopic from

[81] A closely analogous method of formation for glauconite has been assumed by various authorities. See A. Scott, Fourth Report on Colloid Chemistry, Brit. Assoc. Adv. Science, 1922, p. 236.

[82] C. Hintze, "Handbuch der Mineralogie," Band I., Th. 2, p. 1504.

the start and hence invisible to the petrologist. If it is objected that the silica may thus be considered as being present in the metasome in the form of opal and that opal has not been microscopically recognized, it must be remembered that often this metasomatic silica is indistinguishable under the microscope, and even when so visible gives no definite response to optical tests other than by yielding in some cases an "aggregate polarization" that may just as well be due to underlying or adjoining minerals as to the silica itself. Thus it is quite possible that much of such silica *is* present as opal and *not* as quartz, as is usually assumed.

If it be required to account for the presence of definitely determinable quartz grains in our metasome, this demand may be met by assuming the original opal to have been transformed into chalcedony, which is a definitely recognized change, and then into quartz by the process of crystal growth from the chalcedony stage, a process which, though not yet *recognized* as existent in homogeneous minerals, has an analogue in metallurgy and has been referred to at length elsewhere.[83] In case it be further urged that the absence of colloform features from metasomatically altered rocks precludes the idea of colloidal processes in metasomatism, the reply to such an objection is that either the colloidal evidence disappeared during chemical combination and crystallization or that such evidence exists in the altered rock, but has not yet been recognized. Much of the fine-grained and optically unresolvable quartz and the familiar indefinite ground mass formed by metasomatism in igneous rocks may well be colloidal in origin.

Owing to the hydrolysis of the "dissolved" silicate and deposition of the alumina, silica, and lime carbonate, followed by syneresis, the solution (minus a part of its carbonic acid and potassium content) is restored to its condition on first coming into contact with the labradorite and becomes capable of renewed action. Thus, theoretically, a little solution should be able to metasomatically alter a large amount of labradorite, though incapable of continuously forming calcite, and consequently it would seem that the volume of solution to be supplied at the site

[83] H. C. Boydell, *op. cit.*, pp. 55–59.

of metasomatism need only be small. In fact, capillary water, *i.e.*, water held by capillarity in joints, cracks, pores, etc., might well be the cause of metasomatic action.

From considerations such as the foregoing, silicates like the ferromagnesian minerals, the felspathoids, and feldspars, which are difficulty soluble and readily subject to hydrolysis, should be most liable to metasomatic alteration, and petrographic observation shows this to be the case.

FIG. 4. Colloform structure of originally radial-fibrous pyrite from Silverton, Colo., which has been brecciated and cemented by younger vein quartz. After F. L. Ransome.

If gelatinous precipitates and gels have played an important part in metasomatism (and the present writer holds the view that they *have* played an *important* though not necessarily an exclusive or even a dominant part), the question arises whether, taking into consideration the generally evanescent character of the colloidal state, evidence of their having done so would be preserved.

It may be pertinently asked then what are the criteria, if any, of the influence of colloidality in metasomatism, or, in other words, how may we recognize a metacolloid? These criteria have been dealt with elsewhere[84] under the title of "Criteria of Colloidal Origin" and need only be summarized here.

[84] H. C. Boydell, *op. cit.*, p. 54.

The macroscopic evidence is well covered by Rogers'[85] term of "colloform." One of the best pictorial illustrations of colloform features in a hand specimen known to the present writer is that afforded by the beautiful "lithocaustic" representations of "ore structures" occurring in the deposits of the Silverton district, Colorado, given by Ransome,[86] who, however (as was not to be expected at that date), does not refer to their colloidal

FIG. 5. Colloform structure shown by rich gold ore, Camp Bird mine, Silverton, Colo. The base consists of a thin seam of chalcedony and carbonates from which has grown radiating quartz. In it is a dark undulating band with free gold, galena, sphalerite, and an unknown telluride. The wavy bands beyond the quartz are coatings of cryptocrystalline aggregates of quartz, calcite, fluorite, sericite, and a little chlorite. The most conspicuous dark band was called "the worm" by the miners, who regarded it as an indicator of good ore. After F. L. Ransome.

significance. A reproduction of this is given in Figs. 4 and 5. The microscopic evidence involves the question as to how far cryptocrystalline or "amorphous" material produced by gel desiccation can be changed into a microscopically coarsely crystalline

[85] A. F. Rogers, *op. cit.*, p. 518.

[86] F. L. Ransome, "Economic Geology of the Silverton Quadrangle, Colorado," U. S. Geol. Surv. Bull. 180, 1901, Plates XI. and XII.

aggregate. This in its turn raises the point as to whether grain growth and (or) recrystallization, which are accepted by metallurgists as definitely existent processes in metals and alloys, are also operative in a homogeneous mineral aggregate. This matter has also already been treated at length in the reference given.

The commonest microscopic evidence of presumably colloidal origin for a mineral (or rock) is:

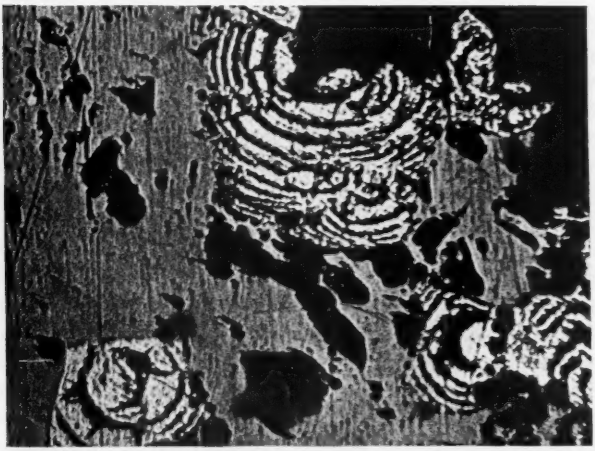

FIG. 6. Colloform concentric marcasite replacing sphalerite and quartz, the latter mineral forming the dark areas. After W. Lindgren, U. S. Geol. Survey Bull. 782. In press. Magnification 130 diameters. A similar structure has been figured and described by Behrend* in ore from the cupriferous deposit of Arghana Maden in Kurdistan and ascribed by that writer to colloidal influences. Newhouse† has identified the same structure in marcasite from Kokomo, Col.

(1) The presence of more or less (usually the latter) perfect concentric outlines or markings in the body of the mineral.

(2) The occurrence of colloform boundaries or banding (using "colloform" in the sense in which Rogers proposed it, *i.e.*, ". . .

* F. Behrend, *Zeitsch. f. prakt. Geol.*, 1925, p. 33.

† W. H. Newhouse, ECON. GEOL., 20, 1925, p. 61.

for the rounded, more or less spherical forms assumed by colloidal and metacolloidal substances in open spaces").

Together with these, though not of the same diagnostic value, is:

(3) The presence of that modification of columnar and fibrous structure known as "radiate, divergent."

What justification, in fact, is there for assuming that criteria *1* and *2* afford evidence of colloidal origin? In the first place, the existence of a substance in spherical or quasi-spherical form, apart from fusion effects and attrition, may be presumed to be evidence of the exertion of surface tension at the boundaries between phases of more or less plastic material. Excluding the case of the phases being molten as not likely of occurrence under metasomatic conditions,[87] and knowing that rounded forms, though known, are not usual in originally crystalloidal deposits, the inference by process of elimination is that such forms are very largely confined to substances of amorphous or colloidal origin. A probable mode of origin of these is found in syneresis, to which nearly all gels and gelatinous precipitates are subject. This consists in partial segregation of the dispersion medium accompanied by shrinkage, which, under the influence of surface tension, must tend to the production of more or less rounded forms and structures. A gel formed under geological conditions can hardly be thought of as being a compact and continuous mass, like one in a laboratory beaker, but rather as consisting of a number of parts of varying size, which, while generally undergoing the same physical changes, pass separately through these as so many portions of an aggregate rather than as a whole and simultaneously.

In this way a gel under metasomatic conditions will, owing to its inherent plasticity, contain numerous rounded and concentric units. The extent to which this form is retained during solidification and crystallization will be dealt with later.

[87] E. Schubert, *Kolloid Zeitschrift*, 35, 1924, pp. 219–220, has described rounded concentric forms produced on solidification of a solution of sulfanilic acid in concentrated sulphuric acid saturated at 180°. This temperature is, of course, well within the range of hydrothermal action and metasomatism.

If the foregoing applies to a gel, it does so to a much greater extent in the case of gelatinous precipitates, the separate clots of which, owing to the effect of surface tension, undoubtedly assume rounded shapes, which will be distinguishable to varying extent in a subsequently compacted aggregate containing them. There is experimental evidence to show that some gels tend to assume curvilinear forms, both internal and external, during desiccation.

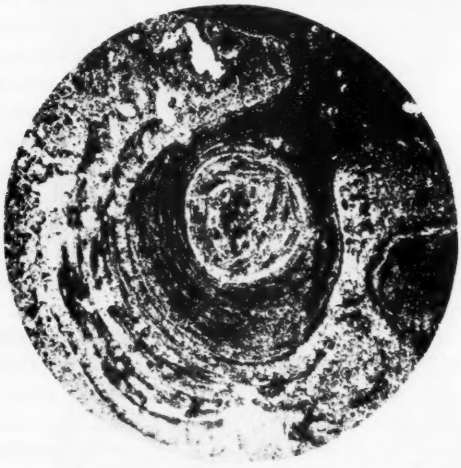

FIG. 7. Colloform structures in siliceous sinter from Yellowstone National Park. The white areas are holes. Ordinary light. × 32.

Hatschek,[88] using spherical segments, cylinders, regular tetrahedra, square prisms, and cubes of *gelatine,* has shown that on *air-drying* the boundaries of all these forms are distinctly curved, cup-shaped depressions are formed, and interior hollow spaces due to internal shrinkage result. It is to be remembered, however, that this behavior is that of an *elastic* gel on drying, and no inorganic gel is as yet known[89] that resembles an elastic gel

[88] E. Hatschek, *Koll. Zeitschr.,* 35, 1924, pp. 67–76.

[89] Private communication from Dr. E. Hatschek.

in this respect. Inorganic gels during drying do not seem to develop the degree of cohesion necessary to give the regular forms yielded by gelatin on drying. *If there is no cracking,* silica gel dries to a porous mass that largely retains its original shape. While air drying might be considered comparable to the desiccation of a gel in the zone of oxidation, it would not be so to conditions of the intermediate and deeper zones.

So far there appears to have been no experimental work done on the desiccation of gels under pressure. The production of concentric forms and colloform outlines or boundaries in gels below the zone of oxidation (where desiccation must, perforce, be thought of as taking place under pressure) is uncertain. Remembering, however, that gels are viscous plastic bodies and that surface development (as evidenced by joints, cracks, pores, etc.) is existent in the intermediate and deeper zones, it seems likely, since surface is always the seat of surface energy in the form of surface tension, that the latter will be there exerted with the consequent production of curvilinear or roughly spherical forms and boundaries. In no case, however, can it be assumed that the existence of such forms is *certain* proof of colloidal origin, though a reasonable presumption is, in the majority of cases, that it is so.

Osmotic pressure effects in media of viscosity ranging from that of ordinary solutions to that of gels is a likely cause of the production of colloform structures under suitable conditions. If a crystal of some colored salt such as ferric chloride, cobalt chloride, copper sulphate, etc., be placed in an aqueous solution of sodium meta-silicate, a portion of the crystal "dissolves," reaction takes place, and the insoluble reaction product or precipitate so produced forms a more or less spherical semi-permeable membrane round the outward diffusing solution emanating from the crystal. Osmotic pressure bursts this "cell," but the solution issuing from the points of rupture forms new cells which in their turn burst and lead to the formation of others and so on till there is produced a branched, cauliflower or polyp like, particolored mass to which the name of Traube's cells or Neptune's Garden has been given. This forms a well-known, effective lecture table experiment of the popular kind.

FIG. 8. Colloform structures in siliceous sinter from Yellowstone National Park. The white areas are holes. Ordinary light. × 32.

FIG. 9. Colloform structures in siliceous ore, 500-ft. level, Waihi mine, Auckland, New Zealand. Black areas are pyrite; the dark line is a crack. The two spherical bodies show three distinct parts not in optical continuity. In the upper one the center is interlocking quartz grains surrounded by an inner ring that merges into separate small grains in places. The outer ring of quartz is less continuous and merges into the surrounding area of quartz grains. Ordinary light. × 32.

FIG. 10. Colloform structures in siliceous ore, 500-ft. level, Waihi mine, Auckland, New Zealand. The lower left represents interlocking quartz grains; the upper center is a single quartz crystal. The curved bands are in general optical continuity with the quartz and consist largely of concentric lines of what resemble dusty inclusions. The whole effect is that of a vestigial structure. Ordinary light. × 32.

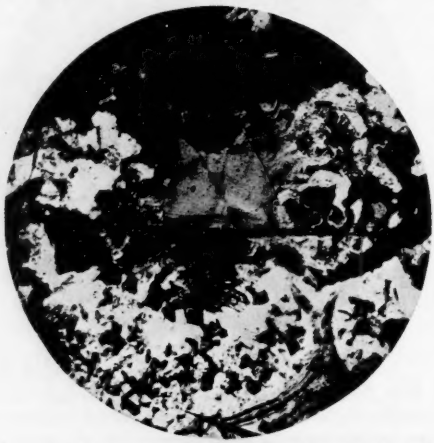

FIG. 11. The same as Fig. 10, but with crossed nicols.

Smith[1] has illustrated a similar structure in chalcedony, and Leisegang[2] has given numerous illustrations of it in agate, and also ascribed its origin to diffusion in gel media. Adams (ECON. GEOL., 15, 1920, p. 656) has illustrated as "colloform gel banding" and "micro-botryoidal gel structure" somewhat similar appearances from Gold Road, Ariz. and Karangahake, New Zealand.

[1] H. G. Smith, "Minerals and the Microscope," p. 67, Plate II., Fig. 5. L. Murby and Co., 1914.

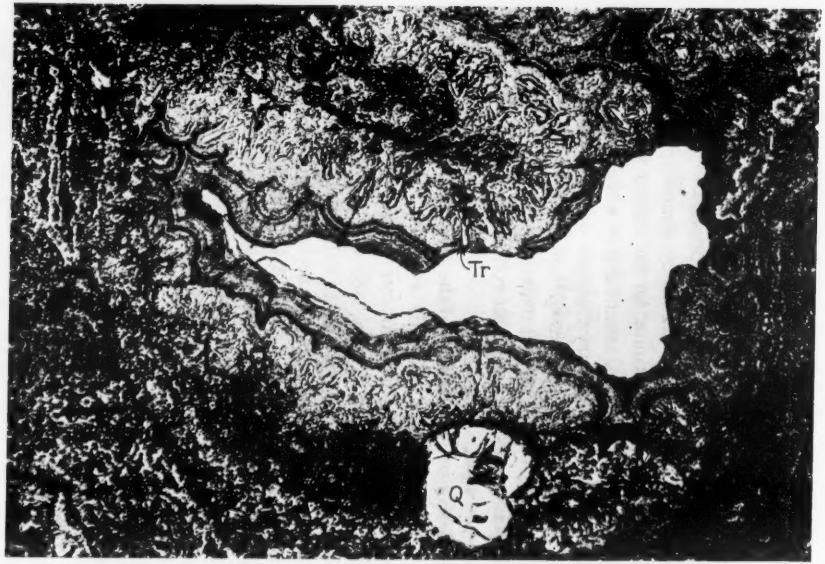

FIG. 12. Colloform outlines and structures shown by lussatite surrounding a vugh in silicified tin-bearing rhyolite of northern Nevada. Tr is a plate of tridymite; *Q* is a residual quartz phenocryst. Parallel light. × 32. After A. Knopf.

The same thing results if a drop of concentrated solution of the colored salt (instead of a crystal) be introduced into a more dilute solution of the reacting substance (say a drop of copper sulphate solution be added to one of potassium ferrocyanide). In much the same way, too, a wavy line (resembling a colloform outline) of insoluble reaction product is formed by the meeting (*i.e.*, at the interface) of two reacting solutions.

The bursting of colloidal membranes by osmotic pressure has been utilized by Knopf[90] to account for the curved and typically colloform particles of wood tin, resembling in some cases broken annuli, which occur in the Tertiary rhyolites of northern Nevada. The present writer has also suggested[91] the same general effect as an explanation of banding in gel material of veins. Undoubtedly, also, it is a means by which other colloform structures could be produced.

There yet remains to be considered the radiate divergent structure. This, according to Dana,[92] is a variety of columnar or fibrous structure and the fibrous character is often very noticeable in thin section. Macroscopically as well as microscopically this structure with a varying tendency to be radiate is met with in a great variety of substances, *e.g., calcite,* some forms of malachite, wavellite, hail,[93] cast iron, urinary calculi,[94] metallic tin, antimony, ammonium chloride, epidote, and most perfectly in asbestos.[95] Reis[96] has investigated this structure in connection with the Ba-

90 A. Knopf, Economic Geology, 11, 1916, p. 658.

91 H. C. Boydell, *op. cit.*, p. 53.

92 E. S. Dana, "A Text Book of Mineralogy," third edition, by W. E. Ford, 1922, p. 182.

93 O. Lehmann, "Melekularphysik," vol. II., 1889, pp. 578–579 and 581.

94 H. Schade, *Koll. Zeitschr.*, 4, 1909, pp. 175–180 and pp. 261–266.

95 S. Taber, *Trans. Am. Inst. Min. Eng.*, 57, p. 70; also *Min. and Sci. Press*, 116, pp. 128–130.

96 Otto M. Reis, "Einzelheiten über Bau und Entstehung von Enhydros, Kalzitachat und Achat, II., Teil," *Geognostische Jahreshefte*, 1918–1919, München, pp. 1–86. This is a Bavarian government publication and is apparently but little known in U. S. A., only the University of California Library having a copy. Reis's work is a most painstaking example of close observation and minute microscopic description. The writer has an extensive vocabulary and this combined with his fondness for the participial construction and long involved sentences

varian agates and other amygdaloidal minerals. He also records a case of its occurrence in rock salt.

Rosenhain[97] has explained the radiate structure in cast metals as due to impeded crystal growth, the crystals growing from outwards inwards, opposite to the direction of heat flow. This suggests, since there is such a close connection between heat conduction and diffusion, that in metasomatism and crystallizing solutions, at ordinary or slightly higher temperatures, growth of the radiate crystals takes place in a direction opposite to that of the diffusing solution, which, on the principle of counter current interchange, would be the direction of maximum food supply for the growing crystals.

Schade, as stated elsewhere,[98] showed that colloidal processes play a large part in the formation of urinary calculii. If the material has strong crystallizing tendency and is pure, the radiate fibrous structure results; but if impurities are present, or if the tendency to crystallization is not strong, then the structure is merely concentric.

Freundlich[99] states that, besides "in the vast majority of cases" lowering the rate of crystallization, the presence of foreign material (impurities) in a solution also alters the shape of crystals. This is due to adsorption of the foreign substance on the crystal faces and the adsorption may be so strong that crystallization is prevented even though the solution be supersaturated. Alteration of shape may arise, according to the same authority, through the degree of adsorption varying in different crystal faces, and thus long needle-shaped crystals be formed of a substance that is usually of quite different crystal habit. This would seem to provide an adequate cause in some cases at least for the radiate structure.

makes his writing difficult for the English-speaking reader. The paper is replete with information for the student of amygdaloidal minerals.

[97] W. Rosenhain, "An Introduction to the Study of Physical Metallurgy," 1914, p. 290.

[98] H. C. Boydell, *op. cit.*, p. 49.

[99] H. Freundlich, *Kapillarchemie*, 1923, pp. 459–466; also "The Elements of Colloid Chemistry," 1924—translation by G. Barger, pp. 100–101.

Lehmann[100] gives the matter of radiate structure in "Sphärokrystalle" considerable attention and quotes many of the older writers on the subject. He considers it to be due to rapid, obstructed crystallization in very viscous solutions and says (p. 380) that there is hardly any substance which with a sufficiently viscous solution and velocity of crystallization will not show the radiate structure (Sphärolithenbildung). It is to be noticed that these conditions of high concentration have been shown to be those favorable to gel formation.

The artificial production of radial as well as concentric forms has been described by Schubert,[101] who obtained them by solidification of a mixture of concentrated sulphuric acid and sulfanilic acid which was saturated with the latter compound at 180°. The solidification, which required from six hours to two days, took place in a vessel surrounded by ice. Shaking was found to prevent the formation of concentric or radial structures, but when undisturbed these developed both at the free surface and on the walls of the containing vessel. There were also formed in the interior of the mixture definite cone-shaped masses which showed either concentric or spiral structure or else radially arranged needles with but few concentric rings.

Owing to the formation of cracks in the solidifying mass, it was assumed that solidification took place with decrease of volume.

The structures could be reproduced by remelting and solidifying the mixture, and Schubert obtained them also in p-tolunitril, in salol, and also in methyl-salicyclic acid. He connects them with Liesegang rythmical crystallization.

It is to be noted again that the concentrations involved resemble those of gels and gel formation.

Bernauer[102] has discussed the radial fibrous structure at some length in connection with colloidal minerals generally and zinc blende in particular. He asks the question: ". . . Ist diese

[100] O. Lehman, *op. cit.*, vol. I., pp. 378–390.

[101] E. Schubert, *loc. cit.*

[102] F. Bernauer, "Die Kolloidchemie als Hilfswissenschaft der Mineralogie und Lagerstättenlehre und ihre Anwendung auf die metasomatischen Blei-zink-Lägerstatten," Berlin, 1924, pp. 14–18; also 44–54.

Erscheinung auf Gele beschränkt, und wie ist sie zu erklaren?" In partial answer to this he considers the radial fibrous structure to be characteristic of crystallization in a supersaturated viscous solution under the existing conditions of which, and in certain small localities those crystals or crystal nuclei whose, orientation is such that the long axis happens to be directed outward from the particular locality toward a freer source of supply of crystallizing material, are specially favored and grow outwards. At the same time, owing to very small supply of necessary nutrient material, the growth of less favorably oriented crystal nuclei is almost completely suppressed.

In this view Bernauer is in general agreement with those of Reis, Rosenhain, and Lehmann, as expressed in the references previously given.

The same writer thinks that radial fibrous structure may be induced in crystalloidal substances by the presence in them of small amounts of colloids and quotes as an example wood tin (fibrous cassiterite), in which the frequent presence of ferric oxide or silica, assuming these to have been originally present in the colloidal state, could have been the cause of the well-known fibrous structure of that mineral.

Daubree[103] produced pronounced concentric, fibrous, and radiate effects in glass tubes by heating them with water to 400° C.

Wyckoff[104] is of the opinion that it depends on the purity of the solution whether a solid is deposited in the form of fibers or not. The presence of impurities alters both the number of crystal nuclei and their rate of formation as well as what may be hazily termed "the surface tension of the solid in its solution." Since the state of aggregation of a precipitate depends partly on these, it follows that the presence of impurities must influence the form that the precipitate takes. In the case of ammonium chloride the presence of various foreign salts in an otherwise pure solution leads to the production of single crystals instead of fibers; in contrast with this the presence of impurities in solutions of other

[103] A. Daubree, "Geologie Experimentale," 1879, pp. 170–171.

[104] R. W. G. Wyckoff, Geophysical Laboratory, Washington—Private communication.

substances leads to fibrous growths. Mr. Wyckoff considers that ". . . there are not two distinct states of matter—one crystalline, the other colloidal. Of those colloidal substances having a solid phase, most are undoubtedy crystalline, the rest are structurally like glasses." In this he would seem to be in general agreement with Freundlich.

From the generality of its occurrence in many diverse substances, the radiate fibrous structure, though suggestive of colloidal tendencies in some cases, perhaps in many, is not a criterion of colloidal origin exclusively.

In summing up the available evidence on the colloidal criteria a question asked by Stansfield[105] may be quoted: ". . . Does the retention of the colloid state give the impress of certain characters which are recognizable without question?" The answer to this must be—so far as we know at present, it does not do so unmistakably. Macroscopically, colloform character affords good presumptive evidence, but is not absolutely determinative. Microscopically, the best evidence is the existence of a concentric structure and, or, the presence of colloform boundaries either isolated or in the form of banding. Neither of these is an infallible criterion.

SUMMARY.

1. The paper deals with the mechanism of metasomatism.

2. To assist the use of international scientific terms requiring no translation, "palasome" and "metasome" are used instead of host and guest, respectively.

3. Consideration is confined to metasomatism taking place below the zone of oxidation and above that of plastic flow, *i.e.*, under pressure conditions.

4. The general relations of thermodynamics, chemistry, and physics to metasomatism are referred to.

5. An attempt is made to define a metasomatic system and the question is raised as to whether a metasomatic change in depth is an isothermal or an adiabatic one.

[105] J. Stansfield, *Bull. Inst. Min. and Met.* (London), March, 1925, p. 27.

6. Three cases are considered according as to whether the metasome occupies a volume greater than, less than, or equal to that of the palasome.

7. The case in which the metasome occupies more space than the palasome is discussed at length particularly in connection with its relation to "the force (linear) of growing crystals."

8. Limitations, foreseen by Becker and Day, to the exertion of "the force of crystallization," but generally overlooked, are quoted.

9. It is pointed out that although the supply of supersaturated solution is a fundamental requirement of the theory of vein formation by the force of growing crystals, the means by which supersaturated solution could be supplied under *geological* conditions have been neglected by the advocates of the theory.

10. Limitations to the exertion of the force of crystallization in vein formation imposed by consideration of (*a*) influence of pressure on melting point, (*b*) influence of pressure on solubility, are indicated.

11. The important difference between uniform and non-uniform pressure is referred to.

12. Influence of pressure on the melting point is held to be of but little importance in metasomatism.

13. Considerable attention is given to the influence of non-uniform pressure on solubility and the absence of treatment of this matter in physical chemistry or geological text books or the literature generally is mentioned.

14. Owing to its geological importance, a mathematical treatment of the subject is given. Two cases are indicated which find homely exemplification in the case of a man standing in running water, in (*a*) the water oozing between the soles and heels of his boots and the ground, and (*b*) that passing under his instep.

15. Owing to lack of the necessary data it is not possible to apply the formulæ deduced to the case of a mineral of common metasomatic occurrence.

16. The essentially consolidating and cementing effect of non-uniform pressure in metasomatic processes is pointed out.

17. After summing up its limitations the opinion is expressed that "the force (linear) of growing crystals" is *not* an important factor in metasomatism generally and in vein formation in particular.

18. The removal of the palasome both by solution without chemical change and by solution accompanied by chemical change is considered at length.

The volume relations connected with solution under pressure are dealt with and the conditions formulated.

19. The importance of surface in connection with metasomatic chemical change is emphasized and the probable influence of adsorption is indicated.

20. The nature of metasomatic solutions and the question as to whether they are molecular or colloidal is discussed.

21. The production of authigenous colloidal material in metasomatism is considered and the likelihood of such, largely as the result of hydrolysis, is accepted.

22. Metasomatic deposition from colloidal solutions both as gelatinous precipitate and as gel is discussed, as is also the means by which necessary supersaturated solutions might be produced.

23. Lindgren's "Gel metasomatism or replacement of crystalloids by gels" is accepted as a de facto geological process.

24. As a specific example of metasomatism there is considered the frequently occurring geological case of the replacement of a labradorite palasome by quartz, sericite, and calcite. It is shown how, by solution, hydrolysis and adsorption, the felted metasomatic aggregate of those three minerals, often observed under the microscope, might be formed, the amount of intruding solution required being only small.

25. Various criteria of colloidal origin are discussed at length and the opinion is given that the retention of the colloidal state does not impart to mineral features which, at the present time, are unmistakably recognizable.

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SALINE LAKES OF THE MOHAVE DESERT REGION.

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THE catchment basins of the Mohave Desert Region have often been examined with a view of developing important deposits of saline minerals. In the past certain of these basins have produced materials of value and some are still being exploited in a desultory manner. Within the past few years they have attracted attention as a possible domestic source of potash. A critical study of these deposits would not only determine their possible importance as saline deposits, but also give much data upon the origin of the similar and perhaps much more important uplifted Tertiary lake beds which occur in the same general area. A thorough understanding of the source and manner of accumulation of the contained salts of these is essential to a proper determination of their value. In this paper certain observations made at various times during the period 1916–1924 are brought together to determine the chief factors involved in the accumulation and concentration of salts in these basins. The basins visited include most of the important and many of the minor ones throughout Southern California and Nevada.

Mud flats, commonly called playas (Spanish=shore) occupy the lowest part of these intermontane valleys that are without exterior drainage. In a few cases the basins are occupied by permanent bodies of water, as Owens and Mono Lakes. In general, however, they are dry for the greater part of the year. During the rainy season (November-May) some of these basins are covered by shallow, ephemeral lakes, but, with the slight precipitation and rapid evaporation of this region, they are of short duration. Others are entirely dry for periods of years and only in cases of

[1] Published with the permission of the Secretary of the Smithsonian Institution. The writer is indebted to Mr. David G. Thompson of the U. S. Geological Survey for much of the data relative to the ground waters of playas as well as other interesting information.

extreme or long continued rainfall are they more than moist. In appearance the playas are flat, vegetationless areas, ranging in size from those less than an acre to some that are square miles in extent. These central areas are bordered by alluvial slopes which, in extreme cases, reach the crest of the encircling ranges (the "pan-fan" stage). The size of the central bare area has only a general relation to the size of the entire basin. Small basins may have relatively large playas while some large valleys are without any. The age of the basin and the rapidity of accumulation are the most important factors governing the size of the central area. This latter factor is dependent upon the topography of the encircling hills, rainfall and to some extent the character of the rocks.

Playas may be divided into two classes with regard to their general characteristics. These are (1) Dry Playas, (2) Wet Playas. This twofold division was first suggested by David Thompson.[2] They correspond to basins that are not water tight and those that are, and this in turn determines their efficacy in retaining the salts brought into the basin. The dry playas are entirely dry, only during periods of excessive or prolonged rainfall in the encircling ranges is water present on the surface for more than a few days at a time. Their surface consists of hard, smooth sun-baked clay without visible concentrations of salt. Drilling in this type of basin has not revealed any bodies of salt below the surface and waters in them are often fresh and potable. Many of the smaller playas belong to this type as well as some of the largest, as Rosamond and Rogers in California and Railroad Valley in Nevada.

The wet playas are salt incrusted areas, covered by a sticky tenacious mud when wet or a light puffy soil when dry. During the rainy season they are often covered by shallow bodies of water and for the greater part of the year they are more or less moist. The water table seldom lies more than a few feet below the surface. In contrast to the dry playas the surface is not hard but covered with a light puffy soil, the so-called "self-rising" ground. Below the surface are strata of moist muds containing isolated

[2] Paper given before the Geological Society of Washington, April 28, 1920.

crystals or small irregular patches of saline minerals. These disappear with depth and saturated brines often give way to fresh water. The concentration of the saline material is largely superficial and rarely extends to any considerable depth. The chief source in the past of commercial salts from these lakes has been in the surface salt crusts. Only in the case of the borate, ulexite, has extensive excavation been profitable. To this type belong Columbus, Rhodes and Teels Marshes in Nevada and Saline and Deep Springs Valleys in California. Searles Lake and other permanent saline lakes may also be classed among the wet playas.

The classification of the playas into dry and wet types also divides them as to their saline content. The dry playas are practically non-saline, while the wet playas carry greater or less superficial accumulations of soluble salts. This relation of the type of playa to saline content has been explained by Thompson[3] as follows: The wet playas are essentially water tight, while the dry playas are those in which the ground water can move freely between basins. The basins that are water tight have their water table near the surface. The surface will then be kept moist by capillary discharge and the salines are carried up. Where the basin is not water tight the water table will be below the depth of capillary rise (about 8 feet) and waters entering the basin from above will remove the soluble salts from the basin. Thompson found that dry playas in general carried less than 2 per cent of soluble material while the wet playas carried from 2 to 20 per cent.

The playas may be classified according to their chemical characters. They may be divided into types based upon the predominance of carbonates, sulphates or chlorides. The chemical composition of the salts will naturally control the character of the minerals that the playa contains.

The following list shows concisely the types of playas and the minerals contained in each type arranged according to their general abundance in the solid salts.

[3] *Op. cit.*

CHEMICAL CLASSIFICATION OF PLAYAS AND THEIR MINERALS.

Dry Playas.	Wet Playas Practically no Salts Present.
Carbonate Playas	Trona, $Na_2CO_3.NaHCO_3.2H_2O$.
	Calcite, $CaCO_3$.
	Thenardite, Na_2SO_4.
	Halite, NaCl.
	Gay-lussite, $Na_2CO_3.CaCO_3.5H_2O$.
	Borax, $Na_2B_4O_7.10H_2O$.
	Pirssonite, $Na_2CO_3.CaCO_3.2H_2O$.
Sulphate Playas	Thenardite, Na_2SO_4.
	Halite, NaCl.
	Glauberite, $Na_2SO_4.CaSO_4$.
	Trona, $Na_2CO_3.NaHCO_3.2H_2O$.
	Gypsum, $CaSO_4.2H_2O$.
	Ulexite, $NaCaB_5O_9.8H_2O$.
Chloride Playas	Halite, NaCl.
	Thenardite, Na_2SO_4.
	Gypsum, $CaSO_4.2H_2O$.
	Glauberite, $CaSO_4.Na_2SO_4$.
	Calcium Chloride, $CaCl_2$.

The carbonate salines are made up predominantly of the carbonate of sodium, trona. The suphates of sodium, thenardite and mirabilite and the chloride of sodium, halite are also present in important amounts. Soluble calcium salts are absent, the lime being fixed as calcium carbonate, or as the double carbonate of sodium and calcium, gay-lussite or, more rarely, pirssonite. Gypsum is also absent. The boron mineral present is always the sodium borate, borax. The double sodium calcium borate, ulexite, is immediately decomposed in the presence of carbonates. Lakes of this type include Soda, Owens and Mono Lakes in California and Fish Lake in Nevada.

The sulphate salines are characterized by an abundance of sodium sulphates, mirabilite, or thenardite. The sodium chloride content and temperature determines which of the above sulphates will form. It is reported that some lakes carry thenardite in the summer and mirabilite in the winter. The surface crust is generally thenardite while mirabilite is not uncommon in the cooler lower layers. Gypsum is often present but generally the double

sulphate of calcium and sodium, glauberite is encountered. The borate mineral is the double borate of calcium and sodium, ulexite. To this type belongs Rhodes, Teels and Columbus Marshes in Nevada and Deep Springs Valley in California.

Lakes predominately chloride in character are rare. Only one member of this type is known to the writer. Bristol Lake in California carries much halite, while gypsum and glauberite is abundant. Sodium sulphate is practically absent while calcium chloride is present in important quantities in solution.

These types are, of course, not sharply delineated. No lake represents the pure type and all transition stages are met with. Single lakes may show one character in one part of its area while carrying a new set of minerals in another portion. Sodium chloride is present in all of these salt bodies. Similarly sodium sulphate is usually present in greater or less amounts. Sodium carbonate, however, is frequently absent.

For a number of years the idea prevailed that the playas were remnants of old extensive lakes and that their contained salts were the residue of these desiccated bodies of water. Some of these hypothetical seas of this region have been given names, but there is no evidence that such large bodies existed in the Mohave Desert Region as there is for Lake Lahontan. Only in a few instances is there any evidence that these playas were ever connected with one another. The diverse character of the salines in the different basins point to independent sources of the salts. The playas are not only distinct in origin, but apparently of quite different ages. Some, like Death Valley appear relatively young, others, like many near the border of the Great Basin are well advanced and in the process of being dissected.

There is evidence for at least three different sources of the soluble materials. These are (1) Rock decay, (2) Volcanic emanations and hot springs and (3) the Tertiary lake beds.

Chemical decay in arid regions is a process that takes place slowly. This is due largely to the scantiness of rainfall and lack of humic acids in the soil. Mechanical decay takes place so rap-

idly that the products of chemical disintegration are almost immediately absorbed by the debris. In a few instances, however, playas are so situated that decomposition products of rock weathering are important sources of saline material. This is especially so when the playa is the sink of a large drainage system. Soda Lake receives in this manner a large amount of material from the Mohave River, a system that receives its chief supply of water and salts from the well watered San Bernardino Mountains. Owens Lake, in a similar manner, receives important contributions from the streams flowing from the Sierra Nevada Mountains. The saline material from such a source is largely sodium carbonate with some sodium sulphate and sodium chloride.

Evidences of recent volcanic activity are abundant throughout the Mohave Desert Region. Recent volcanic cones are especially prominent in the Mono, Death Valley and Bristol Lake Areas. Sulphates and chlorides are common products accompanying volcanic activity. Among the common ones are the sulphates of calcium, gypsum and anhydrite; the chlorides of sodium, halite; potassium, sylvite; and ammonium, salammonite. Sodium borate, borax, and boric acid, sassolite are often abundant. In some cases large quantities of calcium chloride have been found. Sodium carbonate, thermonatrite, has been observed only in small quantities. Salts are also abundant in the hot springs accompanying vulcanism. These consist largely of sodium suphate, sodium carbonate and sodium chloride with sodium borate or calcium chloride sometimes important.

The leaching of the salts from the Tertiary lake beds is the most important single source of the salines in the Mohave Desert playas. Wet playas in the region of the lake beds are invariably rich in salts. These salts have their source in the beds and disseminated masses of saline material in the Tertiary shales. This source supplies large amounts of sodium chloride, sodium sulphate and calcium sulphate with carbonates apparently in only minor amounts. An important constituent derived from these beds is sodium borate. The sulphates are largely derived from

gypsum or glauberite. Some of these old lake beds carry heavy efflorescences of soluble materials and each heavy rain carries large amounts of new material into the basin. The slopes of Mt. Blanco, for instance, are heavily blanketed with salts, the entire surface being covered with the saline "self-rising" ground. These salts are largely sodium sulphate with some sodium borate. Chlorides and carbonates are present only in minor amounts.

Salts from these varied sources are brought into the basin through the medium of the intermittent but ofttimes heavy rains. Only in a few cases are more or less permanent streams the chief agent in this tranportation. A large part of the material is therefore brought into the basin by underground circulation. Upon reaching the basin the salts are brought to the surface by capillary rise and concentrated in the surface layers. This process of capillary rise can, except in basins of unusually rapid accumulation of sediments, keep pace with the rise of the surface. The burial of large bodies of salts will occur only in exceptional cases. This probably accounts for the failure to locate any considerable bodies by deep drilling.

The process of diffusion sets up a migration counter to the rise through capillarity. It is by this downward process of diffusion that the growth of crystals and salt layers in the muds are brought about. The occurence of these crystals has generally been explained as salts that have crystallized out of desiccating solutions and have later become buried. It is difficult however to picture large, well-formed individuals, sometimes a pound or more in weight, forming under conditions of rapid surface evaporation. The growth of these crystals in the muds is well illustrated at Rhodes Marsh. At the time of the writer's visit (May, 1922) the seasonal rains had not yet ceased and the temperature, although not the maximum for this region, had reached 80°–100° F. This playa has yielded a large amount of ulexite and the excavations made for this mineral contained saturated brines. These solutions had, under the direct rays of the sun reached a temperature of about 40° C. The surface layer of muds was also heated

to about this temperature. The muds below the surface rapidly became cooler until at a depth of about 2 feet the temperature was about 15° C. At this point a layer of crystals had formed of sufficient thickness to support the weight of a man. Below this another layer of crystals had formed. How deep these salt strata extended could not be determined. Although some salts had crystallized out in skeleton form in the pools none had sunk to the bottom of the brines but remained as a crust upon the surface of the solution.

The process of the crystallization of salts in the muds is essentially as follows: The surface solution in contact with excess salts is heated to a temperature of 40° C. or more. Below are saturated solutions at about 15° C. Under the impulse of the forces due to this high concentration and temperature gradient rapid diffusion downward will take place, until at a lower level, the solution becomes supersaturated and the salts crystallize out. This process is the well known Soret's Principle. From this first layer the process is continued until it is brought to a halt by the rapid diminishing of the concentration gradient. The formation of the salt layers is therefore a strictly surface phenomenon.

The processes outlined above are the ones active in the true playas, those basins that have never been occupied by permanent bodies of water. The result obtained through the evaporation of large saline lakes is quite different. Only one lake of this type is known in the Mohave Desert region—Searles Lake. Even here the richness and diversity of its salts is due to a combination of favorable circumstances. Salts have been encountered as deep as the deepest borings, over 600 feet. The surface salt crust is as thick as fifty to seventy-five feet. This exceptional development is due to conditions probably duplicated in few if any lakes in this region.

As Gale [4] has shown, the waters entering Searles Basin passed through an elaborate concentrating system, where the Salt Wells and China Lake Basins acted not only as concentrating but settling basins as well. The solutions entering Searles Basin carried

[4] Bull. U. S. Geological Survey, 580, 265, 1914.

a maximum amount of dissolved salts and a minimum amount of detrital material. The small amount of detrital material is evidenced by the meager amount of sediment at the point where the old Salt Wells Valley drainage discharged into the Searles Basin. Soluble materials were, therefore, introduced into the basin in greater relative amounts than in many of the other basins. This soluble material was augmented by a large amount of material from the saline bearing Tertiary sediments of the Slate Range. That Searles Basin derived material from sources other than the Owens drainage can be shown by a comparison of the waters of Owens and Searles Lakes, the waters of Owens Lake being relatively richer in carbonates than those of Searles Lake and only slightly boraciferous. The higher boron content of the waters of Searles Lake is probably due to addition of material from these surrounding sedimentary beds.

From this brief survey of the playa deposits the following conclusions are reached:

1. The chief sources of the salts of the playa deposits are (a) Tertiary saline bearing sediments, (b) Rock decay and (c) Volcanic emanations and hot springs.

2. The concentration of the salines is largely confined to the surface layers.

3. The occurrence of crystals in playa muds is due to the downward diffusion of saturated solutions.

4. The concentration of large bodies of salts are due to special conditions that are seldom duplicated.

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ORIGIN OF PYRITE DEPOSITS OF ST. LAWRENCE COUNTY, NEW YORK.

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THE pyrite deposits at Stellaville, St. Lawrence County, New York, are the most important ones in a general belt extending from the village of Pyrites in St. Lawrence County for about 40 miles southwestward and into Jefferson County. The origin of the deposits has been carefully studied and reported upon by C. H. Smyth[1] and by Buddington.[2] The present purpose is to discuss briefly some of the more prominent features of the pyrite deposits at Stellaville with emphasis upon their origin. The Stellaville deposits occur within the Russell quadrangle, a detailed geological survey of which has been made by the writer for the New York Geological Survey.

The ore deposits at Stellaville lie in "mixed rocks" which are mainly Grenville pyritous ("rusty") gneisses which have been more or less thoroughly injected and soaked by granite and pegmatitic granite and their juices. There are two belts of such ore-bearing mixed rocks separated by a belt of metagabbro. The eastern one of the two belts has metagabbro adjacent to it also on its east side. These ore-bearing mixed rocks are well foliated. They strike north-northeast, and they dip 20° to 40° west. The mixed rocks are rather variable in composition, but they are nearly everywhere very acidic, micaceous, chloritic, and graphitic. A thin section of fine grained, greenish gray wall-rock from close to the so-called "Anna ore body" shows by volume percentages: quartz, with wavy extinction, 61; chlorite, 30; biotite, 5; phlogopite, 1; graphite, 2; pyrite, ½; apatite, ½; and very little zircon. Another thin section of rock from near the same ore body is gray, fine to medium grained, and contains (by volume): quartz, 56; oligoclase, 15; biotite, 11; scapolite, 8;

[1] N. Y. State Mus. Bul. 158, 1912, pp. 143–182.

[2] N. Y. State Defense Council, Bul. 1, 1917.

phlogopite, 4; pyrite, 5; apatite, ¾; and zircon, ¼. A thin section of the medium to moderately coarse grained, granular, good ore from the Anna ore body contains (by volume): pyrite, 45; quartz, 27; orthoclase, 23; and biotite (mostly altered to chlorite), 5. Graphite not uncommonly occurs associated with the ore. Some of the pyrite has fairly good crystal boundaries, but it is mostly very irregular, filling around, and occupying cracks in and between, other minerals. Some slides show dendritic forms of pyrite. The pyrite was evidently the last, or nearly the last, mineral to develop in the ore. It is an important fact that moderately coarse grained pegmatitic and silexitic rocks are also rather commonly and intimately associated with the ore-bearing rocks. Smyth[3] has described various facies of the ore and associated rocks similar to the above, from the Stella shaft.

The western one of the two belts of ore-bearing Grenville-granite mixed rocks contains but one ore body, the so-called "Stella vein." It averages 10 to 12 feet in thickness; it lies parallel to the foliation of, and is not sharply separated from, the mixed rocks; and it dips 20° to 30° west. This mass of ore has been worked 900 feet down the dip, and 1,100 feet along the strike. The eastern one of the two belts of ore-bearing mixed rocks contains a series of four or five parallel ore bodies ranging in thickness from 6 or 8 feet to 18 or 20 feet. These ore bodies are separated from each other by belts of mixed rocks ranging in thickness from about 75 to 100 feet. These sheets of ore, like the Stella ore body, lie parallel to the foliation of, and are not sharply separated from, the enclosing rocks. Mining has reached fully 600 feet down the dip, and nearly 2,000 feet along the strike. The two ore-bearing belts of Grenville-granite mixed rocks are about one-fifth of a mile apart at the surface, and about 850 feet stratigraphically. The ore averages about 20 per cent. sulphur, and it is concentrated to 40 per cent.

According to Smyth the pyrite ore was formed very late during the processes of the granite and pegmatite intrusion and injection of the Grenville gneiss; the source of some of the ore may have been the Grenville "rusty" gneiss; and the main

[3] *Loc. cit.*, pp. 156–158.

source of the pyrite was magmatic solutions or emanations given off by the cooling granite and pegmatite. The processes as described by Smyth [4] were rather complex. Since he has so carefully considered the problem of the genesis of the pyrite deposits, the present writer hesitates to express any difference of opinion on the subject. He will, however, venture to mention one important point of difference, namely, that the main source of the pyrite was the Grenville pyritous ("rusty") gneiss rather than the cooling granite. At least two important field facts support this view: (1) the never failing association of considerable bodies of Grenville pyritous gneiss with the ore not only at Stellaville but also in the various other districts as well; and (2) the absence of anything like bodies of pyrite ore from all other types of mixed rocks including both Grenville and gabbro which have been thoroughly injected and soaked with granite and pegmatite. According to this view the pyrite simply was taken into solution by the penetrating granite and pegmatitic liquids or vapors, carried to higher levels, and there deposited in more concentrated form. The deposits are, in reality, pyrite-rich pegmatites parallel to the foliation of, and not sharply separated from, the country rock. The pyritous Grenville gneiss, where considerable depth is taken into consideration, is believed to have contained sufficient pyrite to account for such a mode of origin of the ore deposits. The explanation of the ore genesis is much simpler than that advocated by Smyth, and it is somewhat similar to that recently suggested by the writer [5] to account for certain magnetic iron-ore deposits of Clinton County, New York. If the pyrite ore was largely due to sulphide emanations from the cooling, intruding granite as advocated by Smyth, it is difficult to understand why pyrite deposits did not also form where types of rocks other than the Grenville pyritous gneiss were intimately injected by granite and pegmatite on large and small scales within the Russell and adjoining quadrangles.

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[4] *Loc. cit.*, pp. 164–182.

[5] ECON. GEOL., vol. 14, 1919, pp. 509–535.

AN EXAMINATION AS TO THE INTERGROWTH OF CERTAIN MINERALS.[1]

W. H. NEWHOUSE.

RECENT writers have sought to explain certain mineral intergrowths by a theory of unmixing.

Schneiderhohn [2] especially has pointed out the similarity between certain metallurgical intergrowths formed by unmixing of an unstable solid solution and some of the mineral intergrowths found in polished sections of opaque minerals.

The explanation of unmixing of an unstable solid solution has been extended to explain the ore mineral relations. An example of this is the familiar occurrence of small elongated blebs or masses of chalcopyrite and pyrrhotite in sphalerite. The small inclusions are frequently arranged along crystallographic lines in the sphalerite.

In some polished sections of ore from Angangueo, Mexico, small elongated inclusions of an unknown galena white mineral occur in pyrargyrite. Frequently they are strung out in parallel rows apparently following crystallographic lines. These inclusions also occur in tetrahedrite but not along parallel lines as they do in the pyrargyrite. The pyrargyrite is later than the tetrahedrite. An area of the small inclusions with a definite boundary may be included partly in the tetrahedrite and partly in the pyrargyrite. The inclusions could not have been inherited from the tetrahedrite by the pyrargyrite for, as was mentioned, the arrangement is different in the two hosts. Replacement of the tetrahedrite and pyrargyrite by the galena white mineral is suggested as the explanation of this intergrowth.

Sphalerite ore from Clear Creek, Colorado, shows quartz veinlets cutting the sphalerite. Occasionally chalcopyrite occurs

[1] Presented before the Society of Economic Geologists, New York meeting, May, 1925.

[2] Schneiderhohn, H., "Entmischungsercheinungen innerhalle von Erzmischkristallen und ihre Bedeutung fur Lägerstattenkunde und Aufbereitung," *Metall. u. Erz.*, vol. 19, 1922, pp. 501–508 and 517–526.

in these veins. Many small inclusions developed partly along crystallographic lines are found in the sphalerite near the quartz—chalcopyrite veinlets. With a high power objective an exceedingly large number of very minute inclusions may be found in the sphalerite along a narrow border of part of the veins. Occasionally some appear at a distance from the vein. This occurrence of chalcopyrite inclusions in the sphalerite, clearly related to chalcopyrite veins can best be explained by replacement.

This replacement of one sulphide by another takes place in many separate centers. The reason for this is not clear. No veinlets connecting these small blebs could be seen in either case described.

The control by cleavage or other crystallographic planes of this type of replacement results in the structures somewhat similar to those formed in unmixing of solid solutions in metallurgy. This being true, it would seem that experimental evidence is necessary before such intergrowths can be attributed to unmixing.

The unmixing of certain solid solutions at lower temperatures than those at which they were formed is a well established fact in metallurgy. Some mineralogical intergrowths have doubtless been formed by similar processes. However, it appears that the criteria which have been used to distinguish them are inadequate. It is possible that other criteria than the experimental may be discovered from some cases such as peculiarities of the individual lenses, a uniform quantity of the unmixed phase over large areas of the polished section, etc.

The occurrence of minute inclusions of one mineral arranged along crystallographic lines in another can not be used as a criterion for an unmixed structure. Replacement may form similar intergrowths.

The replacement may proceed within a host sulphide crystal so as to form small separate masses arranged along crystallographic lines with no connecting veinlets visible with the highest power of the microscope.

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RELATION OF VOLCANIC DIKES TO OIL-BEARING FORMATIONS OF SOUTHERN ECUADOR, SOUTH AMERICA.[1]

GEORGE SHEPPARD.

THE association of volcanic instrusions and oil-bearing formations is not common in the recognized oil regions of the world and, as a general rule, such areas are not considered to be of great value for petroleum. Scientifically, however, these occurrences have a distinct value and it often happens that a detailed investigation of such phenomena in the field results in the securing of important data relating to the nature of the contemporaneous formations of the same region.

If, as is usually the case, seepages of oil are found in the sedimentary rocks near the contact of an igneous intrusion, the oil is either indigenous to the stratified deposits or it has migrated from some other source through a channel caused by the intrusion. Further, if it can be ascertained definitely that the oil is indigenous to the formation intruded by the igneous rock the possibility at once arises of productive areas in the same formation and in some distant territory where intrusions do not occur. In this connection, however, due consideration must be given to the normal phenomena of lateral variation and overlap, which are not infrequently met with in the sediments of Tertiary age, such deposits being found along the littoral of southern Ecuador.

Too much attention cannot be paid to the minor changes or alterations in the stratified rocks which have been induced either by contact or by regional metamorphism. Such variations are often overlooked, or indeed missed altogether, by the geologist in his search for "structure" or other attractive "indications," and it is to be feared that many large concessions have been se-

[1] Courtesy of International Petroleum Co., Ltd. and Anglo Ecuadorean Oilfields, Ltd.

cured in the past which have been proved to be quite useless for exploration by reason of the presence of either concealed, or even exposed, igneous masses. Outcrops of igneous dikes usually indicate that they are simply offshoots of a deeper seated mass, and the surface exposure by no means limits the extent of the parent intrusion. The presence of attractive folds in the vicinity of volcanic dikes also should not be taken too seriously, as these are often the direct result of an intrusion in close proximity.

The contact of sedimentary rocks with true volcanic plugs has been noted in Mexico and the close association of seepages with the volcanic plugs of Cerro de la Pez and Cerro de la Dicha was the direct cause of the discovery of the Ebano field in Mexico. A complete summary of these occurrences is given by Day.[2] According to De Golyer [3] "the principal function of igneous intrusions in the accumulation of oil is believed to have been the formation of channels through which the oil has been able to migrate into the overlying formations and even to reach the surface. A secondary and relatively unimportant function of intrusion is believed to have been the formation by brecciation and metamorphism of reservoirs capable of containing oil."

In any attempt at the solution of the many problems connected with the distribution of petroleum in the peninsula of Santa Elena, Ecuador, one important geological fact, viz., the intimate association of saturated oil sands with the known areas of igneous intrusion is of great significance.

THE ROCK FORMATIONS.

For many years an interesting controversy has been in progress regarding the geological age of the formations occurring in this part of southern Ecuador.[4] The Guayaquil Limestone, forming the well defined range of hills known as the Cordillera de Chongon, is of undoubted Cretaceous age, this having been established

[2] "Handbook of the Petroleum Industry," p. 64.

[3] De Golyer, E., Econ. Geol., Vol. X., 1915, p. 661.

[4] "Cherts and Igneous Rocks of the Santa Elena Oilfield, Ecuador," Joseph H. Sinclair and Charles P. Berkey, New York, N. Y.

many years ago by Dr. Wolf, who discovered Cretaceous fossils in the rock.

Acting upon this stratigraphical evidence it has been assumed by several subsequent observers that certain other formations, having a similar lithological aspect and constitution to the above, are of the same geologic age. The particular areas referred to include the extreme westerly point of Ecuador (La Puntilla of Santa Elena), Punta Carnero and other masses in the same locality, all of which certainly bear a strong resemblance to the true Cretaceous strata of the Cordillera de Chongon. In the opinion of the present writer, however, no Cretaceous rocks have been definitely determined along the "littoral" of southern Ecuador, and the similar formations referred to above (usually veined by chert and enclosing large masses of indurated shale) are probably lower Tertiary sediments which have been profoundly altered as the result of intense metamorphism and the dislocation consequent upon episodes of igneous intrusion.

A glance at a large scale map of the Santa Elena peninsula in which all volcanic dikes, associated metamorphic rocks and "pozo" (hand-dug well) areas are indicated shows how close the relation is between intrusive masses and the known oil-producing zones.

Following the principal chert and indurated shale outcrops near the igneous dikes, and practically everywhere in the vicinity of these intrusions and their zones of metamorphism, the small native-dug pits are clustered in great numbers. In occasional examples also, deeper wells have been completed by the more up-to-date drilling methods.

Mr. H. Cunningham Craig expresses the opinion that[5] "the older Tertiary strata, a petroliferous series, lie upon and are folded against, a solid mass of oceanic strata of Cretaceous age. These oceanic rocks are largely siliceous, very fine grained and not very porous, but are much fractured and faulted by the effect of the movement which has compressed the Tertiary strata into sharp folds. . . ."

[5] H. C. Craig, "Oil Finding," 1920, p. 81.

In this connection the same author considers that the oil (from the Tertiary formations) has migrated downwards, and has accumulated in the harder oceanic formation. From the evidence collected by the present writer, however, during the course of a detailed geologic survey of the Tertiary formations in a district considerably to the north of the one under consideration, there appears little doubt that the hard, limestone-like masses of rock occurring sporadically throughout the Santa Elena peninsula are the indurated representatives of the lower Tertiary "gredas" or clay shales, such forms having been induced by the intrusion of post-Tertiary dikes.

In support of the above observation it can be mentioned that along one portion of the coast to the north of the region under discussion a large volcanic dike occurs which has intruded typical lower Tertiary shales. At the point of contact the metamorphosed rocks are identical with the indurated shales found at La Puntilla, Punta Carnero, and other well-known localities of this region. These altered formations are also veined by cherts and allied siliceous aggregations, and thus present precisely similar features to the rocks found in the peninsular area. Furthermore, it is possible to observe a gradual change or transition from the hard, flinty, metamorphic rock to the normal type of clay shale, the whole series occurring in the cliff sections within a distance of a few miles.

The unaltered shale, it must be noted, occupies the same stratigraphical horizon as the hard, almost siliceous type, that occurs near the intrusion. Although chemical analyses have not yet been made of the principal lithological members of the Tertiary formations of Ecuador, one must not lose sight of the possibility that the finer shales are calcareous in composition. Most of these deposits were derived primarily from the denudation of a large Cretaceous land mass to the northeast and, as a consequence (and from what we know of the undoubted Cretaceous rocks of this region at the present time) it must be assumed that the Tertiary shales contain a fair percentage of siliceous limestone in a detrital condition. By the metamorphism of such a deposit as

the above, therefore, the great similarity of the altered rocks to a true siliceous limestone can be the more easily appreciated.

DEFORMATION AND OIL OCCURRENCE.

Reverting to the immediate Santa Elena district, the Quaternary raised beaches or "tablazos" [6] cover, or have covered, the greater part of the Tertiary land mass of southern Ecuador, and erosion remnants of these accumulations are greatly in evidence near the town of Santa Elena. Below this superficial formation a greenish grey sandstone is found which passes laterally into sandy shales and in certain localities this formation is saturated with a heavy, dark-colored oil. As has been mentioned by Mr. Cunningham Craig the above sands and shales are distorted and crushed to such a degree that it is almost impossible to map the district with accuracy, and any idea regarding the original attitude of these beds can only be put forward with the greatest reserve. Particularly in the vicinity of the volcanic intrusions are found local crush belts and areas of overthrusting in which the areno-argillaceous rocks have been literally pulverized or resolved into an amorphous and loosely consolidated mass of non-descript material.

From the standpoint of petroleum it is important to note that the most saturated oil sands occur in the above excessively shattered areas, these often being in close contact with the actual dikes.

Considering the subject from its more regional aspect a comparison must be made between the oil bearing sands of this district and the similar deposits of the Ancon area (this being adjacent to the southeast). Along the south coast, *i.e.*, from Punta Ancon to Punta Mambra a well developed sequence of exposures is presented, the respective strata dipping generally to the east.

A curious, and almost unique, feature of the clay shale series (which are petroliferous in this area) is the presence of crush zones of considerable magnitude, and there is reason to believe that they attain appreciable thicknesses in their respective hori-

[6] T. O. Bosworth, "Geology and Palæontology of Northwest Peru," 1922.

zons. These crush zones appear to have been formed by a series or a repetition of local overthrusts and recumbent folds especially where the harder sandstone beds have overridden the softer or less "competent" argillaceous deposits. Where this tectonic movement has taken place the detrital element of the clay strata has been resolved into a heterogeneous mass, in which are included Andean pebbles and other rocks foreign to the region under consideration. It thus appears that during the period of maximum tectonic movement (when most of the lower Tertiary formations of this area were compressed), the overfolded argillaceous beds took the greater part of the strain and acted, in effect, as a thoroughly efficient gliding plane of considerable areal extent.

From the general attitude of the beds comprising the series exposed in the Ancon territory it must be assumed that they form, or have formed in the past, the easterly flank of a large anticlinal fold having a general axial trend to the north and south. The following important points are therefore worthy of consideration:

(1) The cause of the uplift of the Ancon area.
(2) The possible definition of the westerly flank of the Ancon anticline.
(3) The presence of oil both in the Santa Elena peninsula, and in the Ancon area.

As all three are probably connected stratigraphically, structurally and genetically, it is necessary to discuss each one in its fundamental relation to the others.

Ancon Uplift.—In the first place it is the opinion of the writer that the principal uplift in the Ancon region took place in post-Pliocene time, and that this was caused (and closely followed by) a series of regional tectonic movements which were succeeded by a brief phase of vulcanicity. During this latter interval of time an extensive series of igneous dikes were intruded into the earlier Tertiary sediments thus causing them to be violently contorted, locally uplifted and metamorphosed along the respective zones of contact. These volcanic episodes in the geological history of southern Ecuador are by no means rare, and it is now

known that the Tertiary formations of this country are frequently penetrated by dikes of post Tertiary age. This fact is of striking contrast to the contemporaneous deposits of Peru where similar intrusions are unknown.

That portion of the volcanic belt which concerns more particularly the Santa Elena region extends roughly from La Puntilla towards the east and north and in the localities where the dikes occur (and there is an extensive series in this district) the intruded strata are highly metamorphosed, the resulting form of alteration consisting chiefly of indurated shales veined by chert. The area of intrusive phenomena, therefore, represents from the viewpoint of regional tectonics, a highly disturbed axial zone of what can be termed the Ancon anticline.

The Westerly Flank.—There is reason to believe that shortly after the close of the Tertiary the westerly flank of the above structural fold existed possibly as an extensive land mass which became subject to the usual forces of denudation and erosion. Subsequently to this phase of geological history, however, the greater part of this land mass became submerged beneath the oceanic waters of that period. Thus it is, therefore, that only the more resistant units of this once extensive terrain are found at the present time, viz., the flat-topped headland of La Puntilla, and other similar lithological outliers. The wide-spread regional depression referred to above, which occurred soon after the close of the Tertiary period, was followed by one of differential uplift, as a tectonic result of which the present Ancon area was elevated and the more distant fringes intruded by a contemporaneous series of volcanic intrusions. At this time, also, most of the stratigraphically younger beds of the Tertiary series along the axial zone were removed by the abnormal forces of denudation and erosion which undoubtedly prevailed. In the succeeding Pleistocene period a resuscitation of the tectonic oscillatory movements took place along the coast belt which resulted in an almost complete submergence of the above land area, with the exception of the more prominent elevations. During this period, also, when the unique "tablazos" or raised sea beaches, were formed

in the shallow seas fringing the coastline of that time, an interval of comparative tectonic stability ensued which was followed by a gradual uplift of the eastern flank of the above-mentioned geo-anticlinal structure.

Apparently this uplift (which is probably still in operation at the present time) materialized in several defined phases of deposition, each of which is indicated by a tablazo terrace, separated by varying intervals of vertical distance. Thus, with the exception of enormous areas removed by erosion, the present land surface is defined.

Oil in Santa Elena and Ancon Areas.—The final point to be considered is the presence of oil in this region and by what means or natural processes this substance has been preserved, or accumulated, since the consolidation of the Tertiary sediments.

The Ancon series of deposits (named after the settlement of Ancon, and found in its immediate vicinity) extend also over the greater part of the Santa Elena peninsula proper. The strata of the latter region consist entirely of soft clay shales intercalated by numerous sandstone horizons. This stage of the Tertiary includes unquestionably the rocks in which the oil has been generated and accumulated. During that period when the folding of the stratified rocks was accomplished, in conjunction with the contemporaneous intrusion of the dikes, the oil was probably segregated primarily by the influence of the thermal agencies connected with the intrusions, and secondarily accumulated in the crushed and shattered zones in the axial area of the principal structure.

As indicated above, a period of intense denudation and erosion then followed, the chief result of which was the removal of the upper members of the series. Thus, in effect, the oil sands or accumulation zones were exposed to the normal forces of subaërial erosion. During this time most of the oil was entirely dissipated from the superficial strata and the residue inspissated to such an extent that it remained only as a thick, heavy crude petroleum, or brea. The above observation, however, only applies to the "pozo" areas of the peninsula.

An important factor then became manifest, a factor which is the resultant of a slight tectonic depression and its subsequent uplift. The then exposed oil sands (*i.e.*, at the beginning of Pleistocene time) were submerged below sea level, and upon their surface a beach or tablazo was deposited. As a consequence of the uplift, the oil sands of Santa Elena were once again raised above the sea and, in addition, were effectively sealed by the presence of a particularly impervious covering of tablazo. In connection with the latter it is of interest to note that most of the hand-dug oil pits in this vicinity invariably pass through a few feet of tablazo material before the actual oil sands are reached.

In the Ancon district, especially upon the axial part of the fold where the lowest strata of the series are exposed, typical oil sands are found in the coast sections. These sands interstratify the clay shales irregularly, are usually discolored by crude petroleum and smell strongly of the same material. These oil sands have a peculiar distribution in the section as they occur sporadically, being separated by varying thicknesses of shale, apparently having very little connection the one with the other. It is worthy of notice, however, that the saturated sands of the Ancon area seem to be more common in the vicinity of local "crush" or "shatter" zones and thus resemble to a slight extent the equivalent deposits on the Santa Elena peninsula.

The fact that the oil sands of the Ancon series are invariably separated by relatively "dry" thicknesses of clay shale suggests:

(1) That too much importance must not be paid to the possibility of upward migration of the oil from a deeper source, and

(2) The oil present in the sands of the Ancon area has probably a genetic origin in the shale members.

In regard to (1) it has already been pointed out that the petroliferous sands of Ancon constitute structurally the axial zone and flanks of a shattered anticlinal fold, the upper beds of which have been removed by denudation and erosion. According to the light of present geological knowledge the actual depth,

or extent, of the Tertiary formations occurring in this fold is unknown, a fact in itself which is of value in determining the ultimate possibilities of the field. Personally, the writer is of the opinion that the Cretaceous limestones underlying the area occur well below the reach of the drill, and if this proves to be correct, the value of the field is enhanced accordingly. The oil, therefore, is governed by the usual conditions normally associated with the structure and, in particular, it will be found to have accumulated in greater quantity in the neighborhood of the crush zones (which form natural reservoirs) as these tectonic phenomena characterize the whole of the area under present consideration. It is highly improbable that the oil has migrated upward from any geological formation older than the Tertiary.

In connection with (2) an appreciation of the conditions governing the unique seepages of oil near the igneous dikes and metamorphozed sediments of the Santa Elena district must be taken into account. Several of the deeper oil pits penetrate the hard, indurated shales veined by chert, most of the pozo areas (*i.e.,* where the hand-dug pits are being operated) occur in association with known intrusions, the oil having been accumulated in the crushed zones of the altered sandstone and shale. From this it appears that in the immediate Santa Elena territory the presence of oil in the disturbed zones has some definite connection with the presence of volcanic dikes, and it may be within the bounds of reasonable hypothesis to suggest that the rise in temperature consequent upon intrusion may have caused a regional separation of the oil which subsequently accumulated under the conditions briefly outlined above.

SUMMARY.

In conclusion, a brief summary of the distribution of petroleum in the Santa Elena peninsula is given, which indicates generally the geographic range of the known occurrences in this region.

Carnero District.—A few ancient brea pits are found near the mouth of the Rio Grande and, near a well defined mass of porcellanite to the west, a series of pozos is being operated at the present time. The pits vary in depth from ten to thirty feet and are

excavated in a greenish oil sand. Close at hand a deeper well (150 feet) has been drilled and this has a reputed yield of ten barrels per day.

Salinas District.—To the east of La Puntilla a few pits have been dug actually in the disturbed cherts and altered sandstones. At this point the strata are crushed and contorted, and, beneath the thin superficial deposit of tablazo, the oil has accumulated in the crush zones induced by the intrusions of the headland. To the east of the settlement of Salinas a group of pozos is being developed beneath a ten-foot layer of tablazo. The underlying sands and shales are typical of the district and are considerably crushed. The pits vary in depth from fifteen to thirty feet and are all grouped around a chert mass.

Ballenita District.—At Punta Suche (near the settlement of Agujeracada) a series of parallel dikes occurs striking generally in a northeasterly direction, thus forming defined ridges or scars into the sea. Altered shales and sandstones are also found in close contact, and in one instance, the contorted porcellanites have been eroded into a natural arch. The dikes are virtually the center of hundreds of hand-dug wells, most of which produce a heavy black oil in small quantity.

From Agujeracada to the southeast, a series of low chert hills indicate the presence and direction of the above mentioned igneous dikes.

To the west of Punta Suche, a series of pits occur along the coast in the greenish sandstone and shale, all being close to the intrusive masses, and to the south fairly deep pits (40 to 60 feet) have been excavated some of which have a reputed production of five barrels per day. These pozos occur in the excessively disturbed area where cherts, dikes, oil sands, seepages and a capping of tablazo are indiscriminately associated. No definite structure (and indeed the same may be stated for the whole of the peninsular area) can be determined as all the rocks are shattered beyond recognition.

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EDITORIAL

IGNEOUS INTRUSIONS AND ORE DEPOSITS OF THE "ZONE OF ROCK FLOWAGE."

In the editorial for March–April, 1925, it was stated that the geologist may crawl, and creep, and climb, to the peaks of Olympus, whereas those supernal heights cannot be reached by Icarian flight.

As an example of the work which the geologist could accomplish for science in his own province may be mentioned the collection and assemblage of information concerning the nature of the earth below the surface. The Greeks believed the interior of the earth to be the abode of lost souls; they conceived it as being six times encircled by gloomy Styx, and to be traversed by Lethe, fiery Phlegethon, together with dread Acheron, Cocytus, and Avernus. Still later, the earlier naturalists conceived it as a molten mass covered with a thin, unstable rock crust. More recent geological work indicates not only a great age, but a definite stability for enormous areas of rocks comprising the crust, and it indicates also that ordinary sediments form a very great percentage of the oldest rock types known. Moreover, the story of these sediments suggests a long sequence of rain and drought, warmth and cold, since the earliest geological time known. To-day, speculation is rife as to the nature of the center, and the geologist is again approached for an expression of opinion. Yet the geologist is only a man as other men. He is possessed of no peculiar powers of divination whereby he may sense correctly the central activities. He has no magic obolus whereby he may persuade Charon to transport him across the Stygian torrent to gain information, nor has he at his call Orpheus to bring him back to earth that he may tell the wonders of the charmed center. On the other hand, there is available to

him the information set out within the wondrous mosaic of outlier and inlier of rock which compose the earth's surface. It is also safe to say that a knowledge of geology is indispensable in such study. Physicists and chemists could not be expected unaided to foretell the peculiar action of forces, when these are associated with the special conditions of enormous mass. Properties of matter unrecognized in laboratory experiments come to light when the matter dealt with is of colossal volume. The action of the great Pleistocene glaciers, the mechanics of igneous intrusion in the Zone of Compression, the peculiar association of life with this great earth, are all striking examples of the unsuspected properties of the earth, when considered in mass. This type of work is peculiarly the province of the geologist and the biologist, and depends upon an application of physical, chemical, and biological principles to the earth as a whole.

The Archæan Complex is the nearest tangible point from which the geologist may approach the problem of mass action within the crust of the earth, and it is possible that the first step towards a solution of the peculiar activities in the " Zone of Rock Flowage " is nearer than we have been accustomed to think, namely, by correlation of the observed forms which igneous rocks and ore deposits assume in vertical succession from the surface downwards. At least, it is a scientific method of attacking the problem as opposed to careless speculation which ignores the evidence of the Archæan Complex. For, if we consider the case dispassionately, it is natural to expect that volcanic extrusions may be related to granitoid intrusions, and that both of these, in turn, may be related intimately to the igneous intrusions which have been formed and consolidated in the earth's crust at depths still greater. It is to be expected, moreover, that a study of such of the latter forms as are exposed to-day as a result of uplift and consequent denudation would throw some definite light on the origin of rocks and activities still more deeply seated than the deepest portion of the " Zone of Flowage " as yet exposed.

The young geologist whose whole experience has been within the " Zone of Fracture " might find little difficulty in considering

that volcanic plugs persevere downwards indefinitely; that dikes and granitoid batholiths have their roots miles below the so-called "Zone of Flowage." On the other hand, the experienced geologist mapping in various areas such as volcanic islands, folded rocks pierced by granitoids, and crystalline schists, must have been confronted continuously with questions such as: "What is the order of sequence of rock forms in any typical vertical section of the earth's crust extending to a depth of twenty-five miles from the surface?"; "What relations exist between the sills of primary gneiss, the 'lit-par-lit' structures, the 'pressure lenses' of pegmatite and of ore deposits, the granitoid batholiths, the dikes, true lodes, and contact deposits, the volcanic necks and lavas?"; "Are these discontinuous, or are they continuous with each other in vertical section?" In other words, are volcanic necks, dikes, sills, and batholiths of separate entities, or have they feeders which only need search to locate them; do they all grade and pass one into the other, with definite signs of physical continuity?

Let us look at the matter a little more in detail, as it is one purely geological and observational, and not one to carry hastily to the nearest mathematician. It cannot be by chance that volcanoes discharge their ashes and lavas from chimneys or pipes situated in certain definite positions along young mountain ranges or earth undulations, or that the plateau basalts of Tertiary time were poured over the more protected but sub-parallel areas behind the great front ranges and their attendant volcanoes.

These are the surface manifestations one sees in young mountains on the one hand, and in the more protected earth undulations associated with them on the other. Within both the stable and unstable areas, great inliers of older rocks may be exposed by denudation. In these inliers, leaving out of consideration for the present the crystalline schists and gneisses generally, we note the absence of any sign of volcanic chimney, but instead there is the abundant presence of laccolith, granitoid boss, batholith, and attendant dike. We note also the abundance of true lodes, of "contact" deposits, of veins, stockworks, and "pipes" of tin,

tungsten, molybdenite, and bismuth, the irregular type of ore deposits such as the " Black Ore " of Japan, the gold-silver deposits of Tonopah, Comstock, Mexico, and the great " porphyry " deposits of copper. In many of the " contacts " and " pipes " we note the discontinuity of the deposits and the lack of visible feeders.

It is customary to see sections representing batholiths as though they had no bases, nevertheless the study of the igneous and ore intrusions, which have been formed simultaneously with the production of the crystalline schists in the " Zone of Flowage " does not appear to support such belief.

Dikes, stocks, bosses, and batholiths, together with true cross lodes or veins, occur in the crystalline schists, but so far as the southeastern portion of Australia is concerned, they belong to periods of intrusion later than the formation of the schists they traverse.

If we may be guided indeed by the excellent figures and descriptive text supplied in treatises on ore deposits such as those of Phillips, Beck, Weed, Spurr, Lindgren, and others, it would appear that the ore deposits formed in the schists simultaneously with the development of the latter, constitute a very peculiar group. They are described generally as " bedded " deposits, as conformable with the associated bedding or schist planes, as being lenticular, somewhat suggestive of irregular strings of flattened beads, and as being characterized by peculiar mineral assemblages, as being associated also with strike faults and gliding planes or with zones of strain arranged parallel or sub-parallel to the bedding planes of the associated sediments.

Perhaps the Broken Hill Field may be selected as a famous example.

In this area the sediments observed were originally mudstone, sandy shale, and sandstone, now altered to gneiss containing abundant sillimanite, garnet, and mica, and which have been invaded by igneous gneisses of primary type and of " phacolite " or sill habit, the banding of the gneisses being parallel to the bedding planes of the sillimanite or sedimentary gneiss. These primary

gneisses, moreover, are granitoid, including siliceous and basic types. All are lenticular, and are discontinuous between the bedding planes. The rocks have been closely folded, and search has been made for feeders to the sills without success. Pegmatite sills, both coarsely crystalline and micrographic, are extremely common. They appear to have replaced the associated and altered sediments in great measure. Faults and gliding planes are mainly parallel to the strike of the sedimentary and igneous gneiss, but in places they cross the strike. These may contain pegmatite exhibiting flowage phenomena.

Beyond this area of sillimanite and garnet development lies a mass of mica, andalusite, and chiastolite, schist separated from the former by a strike fault or gliding plane.

In these less altered sediments, lenses or sills of granite or aplite and pegmatite are common, but the granite sills in places possess short, blunt apophyses penetrating the schists for a few yards. No signs of feeders to these have been found.

The ore deposits of the mica schists are arranged parallel to the strike of the schists and sills. They consist of strings of lenses of greisen with tungsten and wolfram arranged *en echelon,* and of lenses of silver-bearing galena, the latter being in a gangue of carbonate of iron.

In the sillimanite area, the ore deposits represent, in part, " pressure lenses " formed in zones of strain and of gliding, and in part also the replacement of closely-appressed dragfolds of sillimanite gneiss, the replacement resulting in the development of pegmatite with green feldspar, quartz of two ages, rhodonite, pyroxene, manganese-garnet, fluorspar, apatite, magnetite, calcite, containing silver-bearing galena, zincblende, copper pyrites, iron pyrites, and magnetic pyrites.

The general appearance of the Broken Hill deposits along certain levels, especially in the South Mine, has a striking superficial similarity to that of the Homestake Mine Lode in Dakota, so clearly described by Paige in a recent number of this journal. Paige, however, does not appear to mention the occurrence of " pressure lenses," which are so characteristic a feature of ore

deposits in areas of close folding within Australia, and which have been developed along strained zones in schists during the later stages of their formation.

Magnetite (with hematite) lodes also exist abundantly at Broken Hill. These are characteristically sills and "pressure lenses" formed in zones of strain. In the sillimanite area they are granular in texture, consisting of magnetite, garnet, apatite, and quartz. In the mica-schist and phyllite area lying ten to twenty miles north of Broken Hill, the deposits of magnetite are coarse in texture, and consist of magnetite and quartz in large lenses with chloritic material.

In all these peculiar "bedded deposits," no sign of feeders has been found; the great ore bodies follow the corrugations in the country, and are even discontinuous, from point to point, in the same zone, with no sign of physical continuity although a common origin is plainly indicated. Crush zones, bedding planes and schist planes, apparently presented no real obstacle to their progress. They followed bedding planes and strain zones, developing lenses therein, but they appeared unable to penetrate the sedimentary beds themselves, except by the insidious method of replacement.

No trace of dikes, stock, boss, nor batholith was observed in the area except as intrusions definitely much younger than the period of the schist formation, and at a time when the rocks in the "Zone of Flowage" had been denuded and exposed in the "Zone of Fracture."

It is not chance that the igneous rocks of this area are of the type of sills or "phacolites" and discontinuous "pressure lenses." It is not chance also that the magnetite deposits are conformable to the bedding and gneissic bands; that they form "pressure lenses" in places; nor is it chance that the famous ore deposits themselves of Broken Hill are great discontinuous replacements of rocks which have been closely folded with the production of drag-folds. Nor must it be forgotten that the Broken Hill Lode occurs in the "lit-par-lit" areas. Moreover, the magnetite and galena deposits have the appearance of igneous rocks themselves,

apparently vested with peculiar powers of entry, replacement, and departure.

Another peculiarity is that, as evidenced in the Broken Hill area at least, the igneous rocks are not individually large.

As the volcano with its lavas, and the associated plateau basalts, are so characteristic of surface activities; as the granitoid boss, the batholith, the laccolith, the dike, the "contact-deposit," the "pipe," the lodes crossing the bedding planes, and containing sulphides and related gangues, are so characteristic of the region somewhat lower than the surface of the period in which they were formed; as the "saddle," the lens, and the replacement bodies, containing sulphides characterize a still lower zone, and are typically independent of igneous rocks, except as they themselves appear to be igneous emanations; as the "primary gneiss," the "lit-par-lit" forms, the sill, the ore deposit forming "pressure lenses," pseudo "saddles," replacement of drag-folds, and other closely appressed sediments, containing sulphides, dense silicates, and anhydrous iron oxides, mark the "Zone of Flowage," what should we expect to be the characteristics of zones progressively deeper, say fifteen to twenty-five miles below the surface?

It is perhaps permissible, at this stage, to infer from these personal field observations, while awaiting the coördination of the facts gathered within other great fields, that igneous rocks begin, in a small way, at depth, and only become relatively great as individuals by an integration, as it were, of innumerable small emanations as they make appreciable approach to the surface.

It would seem that mountain ranges have been formed by: (1) The tendency of the rocks of the crust to "flow" under their own weight. (2) The reaction set up thus towards the earth's surface, or zone of negligible pressure. (3) The excess of strength (in mountainous regions) of this upward reaction over the strength or "bond" of the surface rocks. (4) The rotation of the earth and (5) The enormous length of the time factor during which such "rock flowage" effects may be produced. An undulatory movement is thus set up. A crude analogy may be found in the rhythmically spaced undulations in

a road traversed by motor cars where the road is composed of horizontal layers of differential strength. The layer of weakness in the case of the earth occurs at depths at which the crustal rocks might be expected to flow under their own weight, an allowance being made for variable lateral support. The main point which must not be forgotten in this connection is that the pressure at the surface of the earth is negligible, and that the material from the center attempts to escape, as it were, to the surface, that is, to give rise to vertical motion. This naturally takes on the form of undulations mutually supporting. As in other undulations, the major earth undulations are ornamented with secondary, tertiary, and other undulations, of higher order, the heavier matter tends to segregate itself under the troughs and the lighter in the crests, and the major undulations are of great relative stability. In these activities, very little horizontal movement occurs, except locally, the main work accomplished being in the attainment of relief upward in the form of these earth undulations, whether as continents or mountain ranges, with a slight tendency to creep by " Rock Flowage " over the unstable beds in the crust where the pressure of the superincumbent crust tends to cause flowage in the lower zones. This would be a variable depth in different places, and, moreover, the depth would be variable at the same place at various times, being conditioned by the nature of the structural " bond " or interlocking action binding the rocks together. If the strength of the " bond " of the upper structures exceed the resultant thrust upwards from the weight of the superincumbent mass, no differential vertical movement results, but if the strength of the " bond " be less than that of the upward reaction, then an avenue of escape is presented from the downward pressing weight of the crust. At a great depth this escape from pressure might be expected to take the form of the passage of emanations from a solid mass, or a mass which is appreciably solid during a measurable interval of time. As the surface is approached the relief from superincumbent pressure might be expected to become more pronounced, nevertheless the enormous head under which the

emanations commenced their ascent would not have been expended unless trapped locally in pressure slacks capped by impervious rock types. As the surface is approached, the integration of the innumerable small individual effects would become marked, with the production of distinct igneous masses, and batholiths might be formed with vast powers of uplifting. Nearer the surface, boring and dislocation action might be expected with the formation of volcanoes and lavas.

The study is peculiarly the province of the geologist, and the information yielded by such study would not only furnish results quite as romantic as the most fanciful speculations held in some quarters concerning the nature of the interior of the earth, including the ore deposits of the crust, but it would, in addition, be a grand contribution, on the part of geologists, to the world's knowledge.

E. C. ANDREWS.

DISCUSSION AND INFORMAL COMMUNICATIONS

CAMP BIRD COMPOUND VEINDIKE.

Sir: I have read with much interest the remarkable study by J. E. Spurr, The Camp Bird Compound Veindike, which appeared in ECONOMIC GEOLOGY, March–April, 1925. This important article raises, in connection with the deposits at Camp Bird, a large number of important problems pertaining to the genesis of ore deposits.

May I be permitted merely to make a suggestion on the subject of the arguments set forth by the writer on page 124, on horizontal alternations of ore concentrations and barren zones in the veins.

Mr. Spurr believed himself to be the first to describe a case where this condition was to be attributed to the same cause as the alternation frequently observed in the dip of the vein, that is to say, to a displacement of the walls of the vein fracture; but the displacement has taken place, not only along the dip, but following a horizontal direction (horizontally). Now Moissenet of France many years ago formulated laws relative to the distribution of pay ore in veins, treating specially of cases where a series of sedimentary strata of alternating beds of different nature, *e.g.*, schists and sandstones, is cut by a transverse vein fracture. One of these laws relates to horizontal alternations: "In a vein which, in penetrating strata unequally resistant, becomes sinuous, the rich portions will form bodies parallel to a definite orientation." And the law was explained by the displacement of the walls.

If one looks at the problem in a general way, it is easy, moreover, to calculate that the displacement of the two walls of a fracture, one in proportion to the other, following a direction in

the plane of certain sections of the latter, implies the alternation, in both vertical and horizontal section, of rich "shoots." The pockets of ore form elongated spindles, of varied inclination, in the interior of certain strata. Cases of horizontal or of vertical alternation *alone* then become, in the hypothesis of complex strata which have systematically influenced the formation of the fracture, simply special cases, not to be distinguished from a genetic point of view.

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METASOMATIC PROCESSES IN FISSURE VEINS.

Sir: Today I had an opportunity for the first time of seeing in No. 4, volume 20, p. 388, of your *Journal* some remarks by Mr. H. C. Boydell, of the Massachusetts Institute of Technology, concerning some statements and deductions which appeared in my paper, "On the Metasomatic Processes in Silicate Rocks."[1] That paper was a translation from the German original, published by me somewhat earlier in "Die Naturwissenschaften" (vol. X., p. 145). I may take the liberty of referring to some points in that original, as they appear more clearly there than in the translation. Mr. Boydell remarks that some of my statements and deductions, in his opinion, are apt to be misleading and he discusses these in some detail. He might perhaps have got a clearer impression of my views on metasomatism if he had read the German original of my paper. I am glad of the opportunity, given me by Mr. Boydell, to add some further remarks concerning points which may have led to his misunderstanding of my meanings. I discuss the physico-chemistry of metasomatism, using as an example the formation of potash feldspar from potash mica, which reaction may be expressed by the equation:

$$\underset{\text{Muscovite}}{H_4K_2Al_6Si_6O_{24}} + \underset{\text{Potash}}{2K_2O} + \underset{\text{Silica}}{12SiO_2} = \underset{\text{Feldspar}}{3K_2Al_2Si_6O_{16}} + \underset{\text{Water}}{2H_2O}$$

The reaction may be written:

$$A \text{ mica} + B \text{ Potash} + C \text{ Silica} = D \text{ Feldspar} + E \text{ Water}.$$

[1] ECONOMIC GEOLOGY, vol. 17, March–April, 1922, p. 105.

Mr. Boydell thinks that I assume a constant ratio to exist between the silica *present* and the alkali *added*. That, of course, is not correct and I never assumed such a thing. What I do assume is that silica is present in excess, since all the rocks concerned contain free quartz.

As silica is present in excess over the amount needed for the feldspathization, there is enough silica present to saturate all the muscovite and potash present. We have, therefore, no need to consider the modifications of the equation which might arise from lack of silica, such, for example, as the formation of leucite instead of feldspar. We may, therefore, substitute "Y alkali silicate" for B potash $+$ C silica, and may also omit water, since that is present in excess and our equation reduces to:

$$X \text{ mica} + Y \text{ alkali silicate} = Z \text{ feldspar.}$$

Mr. Boydell then disapproves of the sentence "we are at the same time not bound to any stoichiometric mica formula or any stoichiometric formula whatever." This sentence is an inaccurate translation of the German original where I state, "wobei wir gleichzeitig vermeiden, uns an eine bestimmte stöchiometrische Glimmerformel ode überhaupt an eine stöchiometrische Reaktionsgleichung zu binden."

The reason for *avoiding* a stoichiometric formula in our case is the following: We may substitute the definite numerical values of the members of molecules by the letters X, Y, Z, as the general deductions I give will hold for *any* stoichiometric formula of the reaction. We only need to replace the symbolic letters X, Y, Z by proper numerical values, which are easily found by writing the stoichiometric equation in the manner desired.

When Mr. Boydell says that this is of dubious accuracy, I am sorry to be unable to understand what he means. I am of the opinion that it would have been of very little value to deduce the laws of the reaction only for some special formula of mica. As soon as we wish to discuss the equation for some special stoichiometric formula of some mica mineral and for some special stoichiometric equation, we may substitute the proper numerical values

for X, Y, Z, and these numbers then appear as exponents in the equation:

$$K = \frac{C^x_{\text{mica}} \times C^y_{\text{alk. sil.}}}{C^z_{\text{feldspar}}}; \text{ for instance, } K = \frac{C^1_{\text{mica}} \times C^2_{\text{alk. sil.}}}{C^2_{\text{feldspar}}}.$$

Concerning the next point disapproved by Mr. Boydell, there seems to be some misunderstanding on his part. Of course, I assume, and also expressly state, that both solid mica and solid feldspar are present in contact with the solution, and I show that in that case, and only in that case, we can substitute *solubility* of feldspar and solubility of mica for *concentration* of feldspar and concentration of mica. It is, in my opinion, just the essential point of metasomatism that the mineral replaced and the replacing are present at the same time during the reaction. Therefore, their concentration in the solution must be constant and equal to their solubility. I had indeed hoped that my deductions concerning this most important point would have been clear enough even in the translation, and I am sorry to see that Mr. Boydell needs a somewhat lengthy discussion in order to tell me just the same thing that I, in my original paper, have stated as clearly as I thought possible.

I avail myself of the opportunity to correct two misunderstandings which have found their way into the English issue. In the statement that the concentration of feldspar must *at least* equal its solubility, the words "at least" are misleading and should be omitted; they are not found in my earlier German paper. In the same paragraph I find the statement that the concentrations of mica and feldspar must equal *the sum* of their individual solubilities. Of course, this is a misunderstanding; the words "the sum of" should be omitted; they are not found in my German paper.

I think Mr. Boydell's criticism of my use of the term "solubility" instead of "concentration" must be based on a misunderstanding that would not have occurred had he read my original publication. The use of the *solubility* of two of the components

instead of the *concentration* is just the essential point of my deductions.

The further criticism seems to be based on some similar misunderstanding. Mr. Boydell writes that my deductions may be applied to all cases of double decomposition, and that they are in no way peculiar to those connected with metasomatism.

I think that Mr. Boydell's statement is wrong; my deductions are limited to those cases where at least *one* of the *educts* and *one* of the *products* of the reaction are coëxisting as solid phases during the progress of the reaction (replacement). Only in such cases can we substitute "solubility" for "concentration" in such a manner that the formation of the new mineral under given conditions of temperature and pressure can be shown to be dependent only on the concentration of one substance added in the fluid or gaseous phase. From that I deduce my result that for any process of metasomatism a definite minimum concentration of the substance added is needed, and that the process of replacement will not take place if at least that minimum concentration is not present. For other cases of double decomposition the formation of a solid product is dependent not on the concentration of one component only, but on the *product* of the concentrations of *two* components. I am very sorry that Mr. Boydell has missed just this one point which I thought to be most essential in my paper.

In conclusion, Mr. Boydell says that I assume muscovite to be soluble in water *without decomposition*. Of course, I never assumed such a thing, but stated expressly that I "disregard electrolytic dissociation and hydrolysis, as these factors, though of influence in the quantitative relations (determining the numerical amount of the "minimum concentration" of alkali silicate needed for the feldspathization of mica under given conditions of temperature and pressure), are of no consequence in the present, purely qualitative considerations."

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FORMATION OF PORCUPINE QUARTZ VEINS.

Sir: I have naturally studied with interest Mr. E. Y. Dougherty's contribution to the study of the origin of the Porcupine veins, in your issue of November, 1925. The writer concludes:

> I agree with Spurr that the veins were probably formed from fluids injected into the wall rocks. The veins cut all the rocks of pre-ore age regardless of chemical constitution and manifestly follow the more penetrable portions of the rocks. In these respects, and in their form and structure, they have all the attributes of intrusive mineral bodies. But it does not at all follow that the injection was accompanied by forcible disruption of the walls of fissures. . . . More tenable is the view that vein fluids have assiduously sought the more penetrable portions of the rocks, exerting hydrostatic and vapor pressure against frictional resistance, rock pressure, and gravity, expending force in penetration and chemical dissolution, rather than in disruption of the invaded rock.

The conclusion in the last sentence is still in agreement with my conclusion, in so far as it postulates forcible penetration of the ore solution or ore magma along fissures under telluric pressure. I am even in agreement as to the evidence of replacement, which I have also pointed out in passing. Thus the caption of my Fig. 2 in the article which Mr. Dougherty discusses[1] read: "Photograph of specimen from Hollinger mine, showing angular inclusions of (partly replaced) wall rock." And in discussing this Mr. Dougherty writes, ostensibly in disagreement: "Surely those inclusions have all the appearance of having been attacked by vein substance."

The real and perhaps important point of difference between my views and Mr. Dougherty's is his conclusion that the quartz has been entirely deposited by substitution for original wall rock, while I believe that the major mode of intrusion was filling spaces which the invading ore solution or ore magma made for itself, by virtue of its telluric pressure.

The line of reasoning which leads Mr. Dougherty to reject this last conclusion is the lack of evidence of pressure distortion of the schists on the wall rocks of the veins. He says:

> The veins are simply frozen against undisturbed wall rock, essentially the same as the rock at a distance from them. As one views the char-

[1] *E. and M. J.-P.*, vol. 116, No. 15, 1923, p. 634.

acteristic undisturbed edges of pliable schist in contact with the veins . . . it is difficult to entertain belief that overpowering mechanical pressure, outward from the veins, acted upon the walls of the veins.

It would indeed seem to the thoughtful student that the walls of intrusive masses—veindikes or dikes, or larger magma intrusions—should show the disturbing effect of having been pushed back. Actually in some cases they do, but in many cases they certainly do not. This fact as applied to many batholiths has led Daly and others to argue intrusion of these batholiths by replacement, not displacement, just as Mr. Dougherty is doing for the Porcupine veins. Daly says: "Batholiths and stocks *appear* to have replaced their respective country rocks in the act of intrusion."[2] I have summarized this problem briefly in "The Ore Magmas,"[3] pointing out that volcanic necks also in many cases show lack of disturbance of the intruded strata. The same, indeed, is true of dikes, and may be seen in the figures I copy from Geikie,[4] and in the figure which Daly copies from Weed.[5] On account of this puzzling behavior of intrusive dikes, sills, and other intrusions, both James Geikie and Archibald Geikie inclined toward the view that the intruded rock, which apparently disappeared, has been dissolved and assimilated by the magma, whether granite or basalt. And in a recent issue of the *Journal of Geology*,[6] M. P. Billings described a diabase dike at Medford, near Boston, several hundred feet wide, which he proves has simply taken the place of an equal volume of wall rock, and without pressure distortion of the walls. Mr. Billings says: "Several facts indicate that the Medford dike intruded the preëxisting terrane by means of a mechanism whereby the country rock was replaced rather than pushed aside." The phenomena of dike intrusion are therefore puzzling and do not conform to the rule which Mr. Dougherty imagines.

J. E. SPURR.

NEW YORK.

2 "Igneous Rocks and Their Origin," 1914, p. 10.
3 Pp. 184, 186.
4 "The Ore Magmas," p. 185, Fig. 43.
5 Daly, *op. cit.*, p. 207.
6 Vol. 33, No. 2, Feb.–March, 1925.

SILICIFICATION OF EROSION SURFACES.

Sir: Dr. C. K. Leith includes the area in the Virgnia Horn (and eastward) of the Mesabi Range in his recent paper, "Silicification of Erosion Surfaces," in your JOURNAL.[1]

The cherts which he includes in this silicification are found on practically the whole Mesabi Range for a distance of about 80 miles. Certain phases of these cherts, including some fossiliferous ones, have been described.[2] The remnants of chert which Dr. Leith believes to have originated by the silicification of an old erosion surface show neither bedding nor banding, and, therefore, their interpretation presents unusual difficulties. Since my views as to their formation differ considerably from that of Dr. Leith, may I be permitted to express my opinion in the following lines as to the origin of these cherts?

At the beginning of Upper Huronian time the rocks of the older periods had been eroded to a peneplain in the Mesabi district. As the sea (either fresh water or ocean) covered the district cherts began to be precipitated almost immediately. The Upper Huronian sea seems to have always been ready to precipitate chert as shown by the numerous iron-bearing formations of this period. However, it is safe to assume that the deposition of these formations did not synchronize exactly. In other words, while they were all formed in Upper Huronian time, some began somewhat earlier than others and were completed earlier. In the Mesabi district no very thick layers of chert formed at the beginning of the Upper Huronian, and as soon as a layer had been deposited it was broken up and its fragments became important constituents of the conglomerate at the base of the Pokegama quartzite, which was forming almost simultaneously. It even seems that the tendency to deposit cherts persisted through the conglomerate stage of the Pokegama quartzite, for some cherts surround pebbles of the conglomerate north of Mountain Iron. Moreover, on the East Mesabi, where the Pokegama quartzite

[1] ECON. GEOL., vol. 20, p. 514, 1925.

[2] Gruner, J. W., "The Origin of Sedimentary Iron Formations; The Biwabik Formation of the Mesabi Range," ECON. GEOL., vol. 17, pp. 418–419, 1922.

Gruner, J. W., "Contributions to the Geology of the Mesabi Range," Minn. Geol. Survey Bull. 19, pp. 5–6, 1924.

thins to a few feet of conglomerate, the cherts of the Biwabik iron formation proper seem to be identical with the cherts filling cracks and fissures in the old erosion surface of the Giants Range granite. The following paragraphs contain the reasons for my interpretation of the origin of these cherts:

1. The cherts are of great lateral extent. They are fairly uniform in texture and composition in spite of their variegated greenish, grayish, and reddish tints. They contain minute perfect rhombohedrons of carbonates and microscopic needles of amphiboles. They resemble closely cherts of iron formations, especially those lean in iron (*e.g.*, W. end of Biwabik).

2. The relatively great abundance of chert pebbles in the overlying conglomerate points to an extensive source of chert.

3. There seems to be no real vein quartz associated with the cherts with possibly one exception. All vein quartz observed by me on the old erosion surface is closely connected with the metamorphic and intrusive activities in the slates, graywackes, and greenstone.

4. Where no recent weathering has taken place the cherts seem to have a pretty clean contact with the rocks on and in which they were deposited. The pebbles at the bottom of the quartzite have semi-angular shapes and were derived from the older rocks close by. Yet no indications that they were subjected to extensive chemical decomposition were found.

5. As indicated above, on the East Mesabi Range the cherts filling the cracks and fissures in the granite seem to grade into the Biwabik formation. The very thin Pokegama quartzite (here only conglomerate) coincides with the conglomerate usually found at the bottom of the Biwabik formation.

It is comparatively easy to see how silicification can occur on limestone erosion surfaces as described by Dr. Leith. Difficulties arise, however, in explaining the chemical decomposition of highly metamorphosed slates and graywackes (some of which are highly siliceous), in the Virginia Horn to such an extent that large masses of chert are formed in juxtaposition to the slates and graywackes.

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REVIEWS

Die Gesteinsmetamorphose. By U. GRUBENMANN AND P. NIGGLI. Berlin, Gebrüder Borntraeger, 1924. Pages ix + 539, with 160 text figures.

The present volume constitutes Part I. of the third edition of Die Kristtallinen Schiefer, by U. Grubenmann, the second edition of which appeared in 1910. While the book was in press Professor Grubenmann died, and the preparation of the second volume, which is to give the detailed descriptions of the metamorphic rocks, has become the task of his successor, Dr. Niggli.

The book has been so thoroughly revised and rewritten that the new title given, "The Metamorphism of Rocks," is fully justified. The treatment is no longer restricted to the crystalline schists, but has been broadened to include contact-metamorphism, pneumatolysis, and hydrothermal processes. Weathering, however, has wisely been omitted as not being included in the historic and generally accepted usage of the term "metamorphism."

The nature of the original material from which the metamorphic rocks have been derived and the specific criteria by which that material can be determined are first elucidated. This necessitates giving a condensed account of the character and origin of the igneous, sedimentary, and mixed rocks. A new method of recomputing the chemical analyses of rocks so as to bring out their significance and to make them readily comparable is presented. It is believed by its author (Niggli) to combine the advantages of the methods of both Osann and Becke. These methods have never aroused much interest among English and American geologists, but possibly this new method, which is applicable to all rocks, will meet some acceptance. Its usefulness is probably most strikingly illustrated in this book where it is employed to show what chemical characters determine the development of chloritoid in metamorphic rocks.

The general principles of metamorphism are next developed in accordance with the laws of physical chemistry. Some of the results recently achieved in metallography concerning the deformation and recrystallization of metals are here shown to be illuminating in the study of the kindred features of deformed rocks.

Metamorphism is then considered from the geological standpoint. A sharp distinction is made between metamorphism in the fundamental rocks

(Grundgebirge) and that in the overlying rocks (Deckgebirge). The reason for this sharp distinction is that in the younger metamorphic rocks, as in the Alps, the highly metamorphosed rocks can be positively traced into their unaltered equivalents. In the fundamental rocks this can rarely be done. Some facts, some principles of metamorphism, can therefore be positively established by the study of the younger rocks, and the principles thus established can be used to interpret the metamorphic phenomena of the fundamental rocks.

Metamorphism is classified under two major heads: I, Autometamorphism, in which the transformation is the end result of the working of the process that produced the rock: comprises the autopneumatolysis of Lacroix and diagenesis, cementation, etc., in sediments; and II, allometamorphism, in which the transformation is effected by processes other than those that originally produced the rock.

Allometamorphism is subdivided as: (1) Load and unloading metamorphism (geothermal metamorphism); (2) Dislocation metamorphism; and (3) Contact metamorphism.

Contact metamorphism is so broadly conceived that it includes not only thermal and pneumatolytic contact metamorphism, but also the metasomatic processes of Lindgren's mesothermal and epithermal vein zones. The hypothermal processes had been previously discussed as a form of autometamorphism. From the standpoint of the economic geologist, this treatment of the vein-forming processes can not be considered particularly felicitous, since the mesothermal deposits are more closely related to the hypothermal than they are to the epithermal. There is still an enigmatic gap between the epithermal and the mesothermal deposits, which has been very sketchily treated in the literature of the subject.

The concluding portion of the volume deals with the products of metamorphism in their various facies. The mineral composition is described as a function of the depth zone in which the metamorphism has been effected. It is vigorously maintained that the recently proposed facies classification of rocks is not much more than a restatement of the depth-zone principle of classification of Becke and Grubenmann.

Particularly valuable are the numerous comprehensive bibliographies that accompany the several sections of the book. With a pardonably full representation of Swiss entries, they are nevertheless thoroughly international in scope and include all notable contributions to the subject. This book should prove healthily stimulating to American geologists in showing them how far ahead metamorphic geology has advanced on the other side of the Atlantic.

ADOLPH KNOPF.

American Petroleum Supply and Demand. A report to the Board of Directors of the American Petroleum Institute by a Committee of Eleven Members of the Board. McGraw-Hill Book Co., Inc., 1925. Price, $3.00.

The committee that compiled this report on the future supply and demand of petroleum in the United States consists for the most part of chief executives of various American oil companies and in preparing it has drawn freely on all available sources, such as surveys and reports of government and state departments, universities, consulting experts, private information of various companies, and the results of research of many individuals. The work represents the condensation and critical consideration of a vast array of data connected with the petroleum industry.

The book is divided into three parts. The first contains a general summary of conclusions, followed by extended résumés of the material presented in the latter two parts, and an account of the operation, growth, and development of the petroleum industry. The second and third parts comprise the bulk of the report and relate respectively to the future supply and demand of petroleum in the United States.

The supply part is devoted to a discussion of the amount of oil that can be obtained from various sources. A brief description of the methods by which it can be won from these sources is also included. It is estimated that 5,300,000,000 barrels of crude oil are recoverable by present methods of flowing and pumping from existing wells in proven territory. The production in 1924 is mentioned as being 714,000,000 barrels, and the total production in the United States from the inception of the industry to March 31, 1925, as 7,870,948,466 barrels. It is estimated that for every barrel of oil recoverable by present methods of flowing and pumping at least two barrels remain in the ground, and that when the price justifies most of this oil can be won by methods of flooding, unwatering, forced air pressure, or mining. The quantity so recoverable is calculated to be about 26,000,000,000 barrels. Owing to the great uncertainty involved, no attempt is made to estimate the quantity of oil that will be obtained from fields yet to be found. Neither is it attempted to estimate the amount of oil that will be obtained by drilling to deeper horizons in present producing fields. However, the committee thinks that the oil so discovered will be "tantamount" to the oil found in new fields. Casing head gas is expected to yield the amount of gasoline that would be won from 1,000,000,000 barrels of crude. It is estimated that there are 394,000,000,000 tons of oil shale from which 108,000,000,000 barrels of crude shale oil can be recovered that will produce 25,000,000,000 barrels of motor fuel. It is thought the country's coal reserves would give from 525,000,000,000 to 2,000,000,000,000 barrels of oil and from 92,000,000,000 to 392,000,000,000

barrels of motor fuel. Furthermore, the lignite in the United States will make 70,000,000,000 barrels of oil that will yield 12,000,000,000 barrels of motor fuel.

In estimating the future demand for petroleum, due to the uncertainty of the controlling factors, it is concluded that forecasts beyond 1975 would be highly speculative and that reasonable predictions could not be made beyond 1950. The estimates are largely determined from a series of graphs based on present tendencies, future population, and upon certain curves that indicate future industrial growth. It is predicted that in 1950 there will be about 45,000,000 automotive engines in the United States, of which 37,000,000 will be passenger machines (equivalent to one per family). The total demand for gasoline in that year, assuming present standards of use, will be 455,000,000 barrels, compared to 185,000,000 barrels for 18,000,000 automotive engines in 1924. However, automotive experts are quoted to the effect that when the people demand it, cars going 40 miles per gallon will be made, and that the efficiency of the automotive engine can be increased 100 per cent. It is also expected that the process of "cracking" will be improved, and that instead of crude oil yielding 33 per cent. gasoline as at present, in the future it will give 55 per cent. It is stated that if this has happened by 1950 the demand for gasoline and lubricants that year can come from 500,000,000 barrels of crude run to the stills compared to 643,966,000 in 1924. However, due to the increased yield of gasoline, it is calculated that but 200,000,000 barrels of fuel oil would come from that amount of crude, which would take care of but 30 per cent. of the normal fuel oil demand of 641,000,000 barrels for that year. It is realized, though, that many of the industries now using fuel oil will use substitutes when the price becomes high, and therefore a minimum fuel oil demand curve is compiled, based solely on the requirements of the U. S. Merchant Marine and Navy, as it is thought these could go without fuel oil the least readily. This gives a value of 71,000,000 barrels for 1950.

In addition to these, numerous other graphs are included that relate to future population, industrial growth, power demands, lubricating oils, and rate of depletion of our coal and oil shale reserves, if all gasoline requirements were to be taken from them in the future. The information upon which the curves are based is discussed in the text. In treating of the future energy requirements of the country it is thought that the Diesel engine will come into more prominent use in the future, as it would have the effect of multiplying the available supplies of motor fuel six times. This is based on the statement that the popular gasoline engine has two-thirds the thermal efficiency of the Diesel engine and utilizes but 25 per cent. of the crude, whereas the Diesel engine utilizes 100 per cent. of the

crude. However, the statement that the gasoline engine utilizes but 25 per cent. of the crude apparently does not agree with the remark on page 17 that crude at the present time yields on the average 33 per cent. gasoline.

The most important conclusion reached in the book is that there is no imminent danger of exhaustion of our petroleum reserves. Judged from the estimates given, this probably is true, but the committee fails to discuss the important question of how soon the amount of oil obtainable by present methods of flowing and pumping will materially diminish and the more expensive methods of recovery will have to be invoked, thus causing a marked increase in price of petroleum products. The effect of this on the petroleum industry is not treated, nor how it will influence the estimates of future demand prepared by the committee, for in the preparation of most of these price has not been used as a factor. However, the committee recognizes this and states that estimates that are a function of the influence of supply and demand upon price must be highly conjectural.

The book is concisely written, but some of its material has been summarized three times in addition to being but briefly discussed in the text, and a person reading the book completely will feel that there has been unnecessary repetition. A number of statements in the book apparently have not been carefully checked either with other remarks in the book or with known facts. Attention has already been called to one of these in discussing the Diesel engine. Another occurs on page 224, where, under the general topic of soft coal and lignite, one reads that it is estimated that from every ton of coal distilled there will be recovered 1,100 pounds of coke. It is also assumed that 1,500 pounds of (this ?) coke will perform the same amount of work as 2,000 pounds of coal. The committee does not mention whether the coal alluded to three lines above refers only to coke-producing coals or whether it refers to all soft coals and lignites, but from the context of the book one is led to believe that it refers to all soft coals and lignites. Therefore, one is inclined to question the statement that every ton of coal distilled will yield 1,100 pounds of coke of the quality mentioned above. A similar apparent discrepancy occurs on page 33, where, in attempting to show that the basic price of petroleum has not materially changed in the last ten years, the committee states that the average price per barrel of mid-Continent crude in 1924 and on April 2, 1925, was $1.45 and $1.938, respectively, which corrected for the decrease in the purchasing power of the dollar since 1913 is $0.967 and $1.08, respectively. Evidently this must be an error, else it would imply an improbable dollar inflation of 19.6 per cent. between 1924 and April 2, 1925.

The book, however, is a decided contribution to our knowledge of the

petroleum industry. It represents the careful consideration and condensation of the opinion and judgment of more than 250 individuals and the material presented has been looked at from a large number of different viewpoints. Apparently a due amount of conservatism has been used in the estimates and a strong effort has been made to tackle the problem scientifically. The report contains a wealth of information and statistics and includes abundant references to the literature.

PARKER D. TRASK.

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Economic Geology. By HEINRICH RIES. Fifth Edition, Revised. New York, John Wiley and Sons, Inc., 1925.

The fifth edition of Professor Ries's "Economic Geology" can not fail to be of importance to all who are interested in that science.

The new edition contains some slight changes in subject matter, but is identical in form and scope with the one which preceded it. The number of pages has been reduced by twenty-five through the omission of the lists of plates and illustrations, as well as by condensing the index. Otherwise the paging is the same throughout the two editions. The chapter headings are unchanged except for the substitution of the words "Subsurface Waters" for "Underground Waters."

The most important additions in the new volume are to be found in the references and statistical tables. Some changes are made in the references at the bottom of the pages and new ones are added at the end of each section. Under important headings, such as "Iron Ores," "Copper," or "Ore Deposits," these are grouped at the end of the former list as "supplementary," thus setting apart the latest works on those subjects graphically. The tables giving statistics of production, exports, etc., start where those of the former edition left off and bring the figures up to recent years—frequently to the years 1923 or 1924.

The grouping of so large a number of references on all the topics treated coupled with the recent statistics of the same under one cover is alone sufficient to make the new edition particularly valuable.

W. M. AGAR.

An Introduction to Physical Geology, with special reference to North America. By WILLIAM J. MILLER. D. Van Nostrand Company, 1924, vii, 435 pages.

A new arrival deserves a place among the ranks of elementary textbooks chiefly when it brings into the field new pedagogical methods, an improved organization of material, or a more intelligent system of illus-

tration than those already in use. In these respects, Professor Miller's text appears to differ but little from its immediate predecessor, the second edition of Pirsson's "Physical Geology." A comparison of the two works reveals similarities in the approach to the subject, in the organization of material within the various chapters, and in the selection of photographic illustrations. True, the sequence of the chapters has been changed, but the improvement effected is not clear. In justice to the new book, however, it must be said that its length is well suited to a short and elementary cultural course, and that, to this end, the text is notably readable and understandable. It is on these terms that the work should lay claim to attention.

RICHARD FOSTER FLINT.

Bibliography of Bibliographies on Chemistry and Chemical Technology, 1900–1924. By CLARENCE J. WEST and D. D. BEROLZHEIMER. Bull. Nat. Res. Council, vol. 9, Pt. 3, No. 50, pp. 308, 1925.

This is the third of a series of collective bibliographies prepared by the Research Information Service of the National Research Council, the first being on Geology and the second on Physics. It is not a complete list of published bibliographies on chemistry and chemical technology even for the period indicated, as many of these have so little interest that their inclusion is not justified. Few bibliographies before 1900 have been included. The subjects are divided as follows: Pt. I., General; Pt. II., General abstract journals and yearbooks; Pt. III., Collective indexes of serials; Pt. IV., Special subjects in alphabetical arrangement; Pt. V., Personal bibliographies.

E. B. W.

SOCIETY OF ECONOMIC GEOLOGISTS

The annual business meeting of the Society of Economic Geologists was held at Yale University, New Haven, Conn., on December 29th. A large number of members took part in the discussions which centered largely upon an important method of arranging definite programs for future meetings, and the place and time of future meetings.

The announcement was made that the following officers had been elected for 1926:

H. Foster Bain, *President*
W. H. Emmons, *Vice-President*
R. A. F. Penrose, Jr., *Councillor*
J. B. Tyrrell, *Councillor*

The election of the following members was also announced:

Dr. John Henderson, Geological Survey, Wellington, N. Zealand.
Prof. Johann G. Koenigsberger, Freiburg, Germany.
Dr. Frederic H. Lahee, Sun Oil Co., Dallas, Texas.
Mr. Frederick Byron Plummer, Houston, Texas.
Dr. Henry Caselli Richards, Univ. of Queensland, Brisbane, Australia.
Mr. Robert Speight, Canterbury Museum, Christchurch, New Zealand.
Dr. William L. Uglow, Univ. of British Columbia, Vancouver, B. C.
Dr. Morley Evans Wilson, Geological Survey, Ottawa, Canada.

The Program Committee for 1926 is as follows: D. F. Hewett, *Chairman*, Adolph Knopf, Augustus Locke, B. S. Butler, W. J. Mead.

The Arrangements Committee for the 1926 meeting of the Society, the date of which will be announced later, is as follows: Charles P. Berkey, *Chairman*, J. Volney Lewis, Arthur Notman.

The Society has been invited by the Japanese National Research Council to send a delegate to the Third Pan-Pacific Science Congress to be held at Tokyo, Japan, in the fall of 1926. Dr. C. K. Leith, past president of the Society, was named as representative of the Society at this congress.

The Society will hold an informal meeting at Madrid in May, 1926 during the sessions of the International Congress. Per Geijer was appointed chairman of the committee to arrange for this meeting.

SCIENTIFIC NOTES AND NEWS

H. A. Brouwer, Professor of Geology at Delft University, Holland, and noted for his petroleum work in the Dutch East Indies, has been appointed professor of geology at the University of Utrecht. He will stay at Delft, giving special lectures at Utrecht only.

George R. Mansfield, of the U. S. Geological Survey, recently lectured at the Idaho School of Mines on the areal and structural geology of southeastern Idaho.

W. T. Schaller, of the U. S. Geological Survey and president of the Mineralogical Society of America, recently spoke before the Geological Club of Yale University on the "Rôle of Replacement in the Origin of Pegmatites."

Ernest N. Patty, Professor of Geology and Mineralogy at the Alaska Agricultural College and School of Mines, has been elected dean of the college. He will also continue as professor of geology.

E. M. Butterworth has been placed in charge of geologic work in Southern California for the Standard Oil Company of California.

Hans T. F. Lundberg and Karl Sundberg, of the Swedish American Prospecting Corporation, have received from the Engineering Company of Sweden a gold medal for conspicuous ability in electrical prospecting.

H. S. Lyne, petroleum geologist of Australia, has joined the geological staff of the Standard Oil Company.

Henry Louis, of Newcastle-on-Tyne, England, has recently returned to England after an examination trip in Mexico.

J. P. Schumacher of Holland, formerly connected with the Royal Dutch Shell Company, has opened an office in Houston, Texas.

A. W. Newberry returned to New York recently after a trip to South Africa.

Victor C. Alderson now has an office in the Symes Building in Denver, and will devote his attention to the oil-shale industry.

The Gulf Production Company has discovered through its geologist, L. P. Garrett, a third salt dome at a depth of 800 feet, by means of the

seismograph, drilling through sulphur-bearing cap rock near the town of Fannett, Jefferson County, Texas.

James H. Hance, of the Illinois Geological Survey, has resigned his position there and is to be head of the department of geology in the Texas A. and M. College, College Station, Texas.

Carroll H. Wegemann, R. Clare Coffin, and Ellis A. Hall, recently connected with the Midwest Refining Company, are doing foreign work for the Pan-American Petroleum and Transport Company, of New York City.

Ralph A. Liddle, formerly with the Standard Oil Company in Venezuela, is now with the Pure Oil Company, Mexia, Texas.

George McLane Wood, widely known as the efficient editor of the U. S. Geological Survey, has opened an office for the editing of technical manuscripts at Room 631, Investment Building, Washington, D. C.

Sterling fellowships for research in the Natural Sciences and Humanistic studies have been established at Yale University. These are open to men and women, graduate students or teachers on leave of absence, who desire to carry on studies under the direction of the Graduate School of Yale University. There are two classes: Senior fellowships of $1,000 to $2,500 or more for those who have had the Ph.D degree or its equivalent, and Junior fellowships for $1,000 to $1,500, open for candidates for the Ph.D degree. Appointments are for one year, but may be renewed. For other details and application blanks address the Dean of the Graduate School, Yale University, New Haven, Conn., before March 1.

The International Geologic Congress meeting at Madrid, Spain, will take place from May 24 to May 31, and the excursions will start May 10. Those of chief interest to mining geologists are: A–1, Gibraltar, Algeciras, Northern Morocco, 12 days, leaving Madrid May 10; A–3, Linares and Huelva, 10 days, May 13; B–1, Almaden, 2 days, May 28; C–1, Asturias coal district, Covadonga manganese, 6 days, June 1; C–2, iron deposits of Bilboa, 3 days, June 8; C–3, potash basins of Catalonia, 11 days, June 1 and June 8. Other excursions are listed in the December number of this journal.

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